# A PHOTOVOLTAIC INDUCTION MOTOR WATER PUMP AND FAN DRIVE

by

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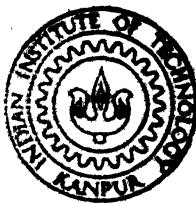
DEPARTMENT OF ELECTRICAL ENGINEERING

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NASEAM HAIDER JAFRI

to the

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Lovingly

dedicated

to

My parents and teachers'
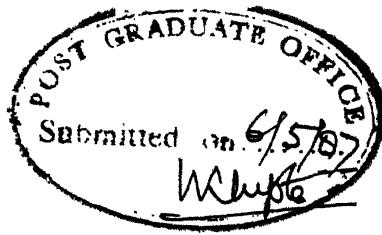
CERTIFICATE

This is to certify that the thesis entitled
'A PHOTOVOLTAIC INDUCTION MOTOR WATER PUMP AND FAN DRIVE'
is a record of work carried out under our supervision
by Naseam Haider Jafri and that it has not been submitted
else where for a degree.

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ACKNOWLEDGEMENT

ABSTRACT

Generally permanent magnet dc motors are used in photovoltaic pump drive. The brushes and commutator require frequent replacement and maintainance. In the present work an induction motor pump drive is proposed, which over comes the above mentioned problems. A maximum power tracker is developed which ensures maximum power input to motor by controlling the modulation index of the inverter. The single phase permanent capacitor motor is used and is operated at good efficiency by using suitable speed control scheme. A single phase inverter is designed with least possible number of power transistors. A P.M technique operating at high frequency is employed to obtain sinusoidal output voltage and current with low harmonic distortion. A prototype drive is built in the laboratory and is tested with fan loads. The performance of the drive is found satisfactory.

CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 *Introduction*

Water is pumped for drinking, irrigation and for the
use in^industry and households. The cost of the water is directly related
to the required energy for pumping of the water from the
ground. The common energy for water pumping is the electrical
energy due to its availability near the site of human
habitation at reasonable cost. However in small villages and
agriculture fields, where conventional power grid supply
is not available, diesel pump sets are used for water pumping.
These pump sets require frequent maintinance and fuel. The
annual running cost becomes principal economy factor. There
is vast need for low cost systems, which requires no fossil
fuel and very little maintenance specially in India due to
its poor reserves of fossil fuels. Such system must employ
reliable equipment to ensure high MTBF (mean time between
failure). The photovoltaic system has the potential to
provide such an alternative. However, initial capital cost of
the photovoltaic pump system is about four times the diesel
alternative, but the difference can be recovered in four
years (assuming no increase in the cost of diesel) [8]. Furth

reduction in the cost of the solar cells is expected due to the large scale production and advances in manufacturing techniques. Therefore the future of such systems is very bright.

Photovoltaic pump system consists mainly three components, electric source which is a solar cell array, an electromechanical converter which is an electric motor and load which is a centrifugal pump. Several pump systems have been developed, which employ dc permanent magnet [7] or wound field motors [9-11]. These drives require frequent maintenance due to replacement of the brushes and commutator. Some authors have suggested ac permanent magnet motor but the reliability of such system at this stage may be considerably poor due to involvement of complex electronics, which eleminates both

In the present work, photovoltaic induction motor pump drive which eleminates both of the above mentioned problems has been investigated. It is a variable speed drive with a maximum power tracker in the inverter circuit, to ensure the maximum use of available photovoltaic power. A single phase transistor inverter with least possible power switches is fabricated and tested on the single phase permanent capacitor induction motor coupled with fan.

1.2 ORGANISATION OF THE THESIS

In chapter 2 the operation and behaviour of solar cell and different motors is briefly discussed. The advantage and disadvantage of various drive schemes and maximum power tracking schemes is also outlined.

In Chapter 3 the proposed drive scheme is described. The operation and design of the single phase transistor inverter is discussed. The principal of the power maximization is also discussed.

Chapter 4 deals with the details of control and protection circuits. The design and operation of the firing, base drive, maximum power tracker and snubber circuits is described.

In Chapter 5 analysis of the single phase permanent capacitor induction motor with voltage source is discussed. The experimental results of the drive are presented. Also some oscillogram of the inverter performance with different loads is presented.

CHAPTER 2

PHOTO VOLTAIC PUMP AND FAN DRIVE

2.1 INTRODUCTION

The conventional sources of energy are used either
directly ~converted into electricity to supply the demand
of energy in present age. The direct use of energy involves
burning fuels such as wood, gas, oil and coal directly for
the purpose of heating requirement or in combustion engine
for the purpose of doing mechanical work. Mostly electricity
is created by converting energy from fossil fuels and
nuclear reactions into electrical energy through the production
of steam and the rotation of a generator. The conversion
precedure is costly and inefficient. Both the cases suffer
from the disadvantage of health hazard due to radioactive
radiation and/or pollution. Since the demand of energy is
increasing at an alarmingly high rate and the conventional
sources of energy are very limited, there is a need of non-
conventional sources of energy which should be economical,
unlimited and free of all types of pollution. The solar
energy is a one of the promising alternative due to its availability all
and easy conversion into electricity without any
any pollution. Despite these advantages photo-volatic energy

suffers from the limitations such as cost of solar cell, the amount of annual sunshine at the site, the time and type of photo-voltaic output and the space required to generate significant amount of power.

Up till now solar cells have been used for satellites, electric calculators and watches, single person airplane, prototype cars, water pumping, water desatination plant and professional radio stations [1]. Small water pumping irrigation projects are most suitable for remote locations in India. A simple photovoltaic water pump drive consists of solar cell module, a motor and a pump. In this chapter these components of drive will be discussed.

2.2 SOLAR CELLS

2.2.1 General:

The solar cell was reported as early as 1941 but it was 1954 when silicon solar cell was announced by Chapen, Fuller and Pearson. The solar cell was widely used in space applications by 1960. By the end 1970's, the production of silicon cells for use in terrestrial applications became dominant factor and hence fast reduction in the cost due to large scale production. The basic principle of operation of solar cells

depend upon 'Photovoltaic effect' reported by Becquerel in 1839 [2-3]. The solar cell converters the sun light directly into electricity and heat plays no constructive part in the process. It is some what puzzling because all conventional methods of generation of electricity involve production of heat.

The best silicon solar cells are made from one carefully grown crystal in which all the atoms are facing the same direction and fit together into a neat three dimensional grid. Multicrystal or poly crystaline cells are less expensive to grow but have a lower efficiency. Amorphous silicon cells promises to be most inexpensive to manufacture because they can easily be produced in thin film but their conversion efficiency is lower than that of single and polycrystaline cells. Beside silicon solar cells, there are some other solar cells having their own advantages and disadvantages. The copper-cadmium sulfied which are inexpensive in production but have low conversion efficiency of 9% and gallium arsenide with an efficiency of 22% are most common [1]. The basic principle of operation of solar cell is outlined below.

In a normal PN junction a small voltage called potential barrier is developed across the junction due to migration of

free electrons from N to P material and reverse flow of holes.
Thus voltage prevents the further flow of charge carriers
and sweeps away all the free electrons and holes from the
depletion region. The number of majority carriers in both
sides of junction will depend upon the level of doping but
the number of minority carriers (holes in N type and electrons
in P-type) will depend upon the light and heat condition. At
the room temperature, there are free electrons and holes in
the junction; these charge carriers either recombine if they
are away from the junction or swept away by the potential
barrier towards their majority concentration. In an unillu-
minated junction majority and minority carrier currents are
equal and balance each other out. This ballance of current
is disturbed when light falls upon the junction. The each
incident photon having energy charge $(h\nu)$ more than band gap
energy E_g of silicon is capable of generating one electron
hole pair. These electrons and holes will be forced apart
by electric field and pushed towards their respective N and P
material provided thickness of junction is small enough and
life time of charge carrier is large enough to avoid recombi-
nation. This movement of electron-hole pair will give rise

to photo-voltaic current. Amount of current and hence power depends mainly upon the intensity of light, temperature and cell area. The short circuit current of solar cell is proportional to the intensity of light and cell area but varies little with temperature, while the open circuit voltage of solar cell is inversely proportional to the temperature and is not effected by the cell area. The open circuit voltage varies little with the intensity of light. The characteristic of solar cell and its variation with intensity of light and temperature is shown in Fig. 2.2.1.

2.2.2 Maximum Power Tracking:

A solar cell array is consists of many solar cells connected in a series/parallel fashion. The array has I-V characteristic similar to that of a single solar cell. Each I-V curve has a maximum power point at which the product of array voltage and current is maximum. It is advantageous always to operate the array at its maximum power point. Maximum power can be tracked by placing an electronic circuit called 'maximum power tracker' between solar cell array and the load; which changes the apperent impedance of load untill the photovoltaic power is maximized. The photovoltaic power
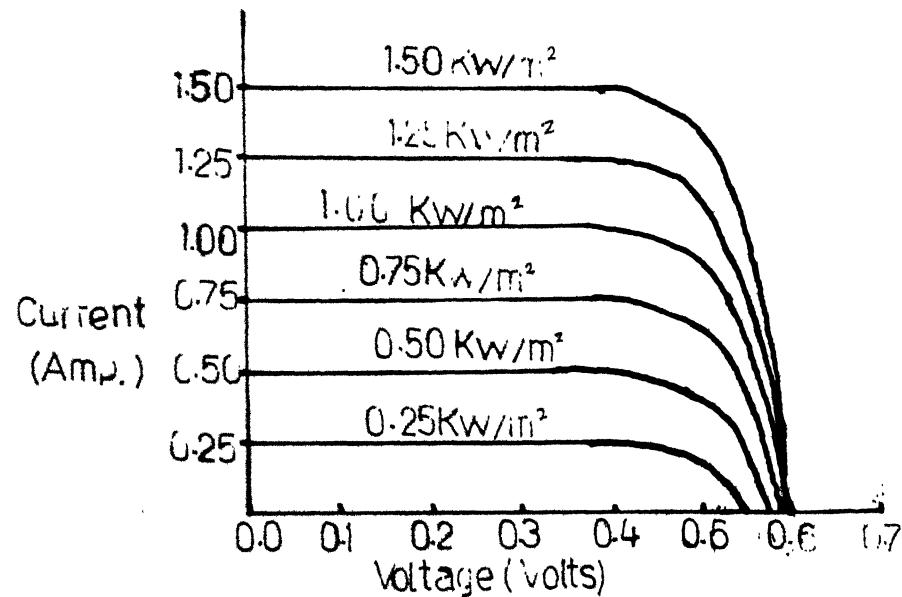
Fig. 2·2·1a Characteristics of solar cell with changing insolation
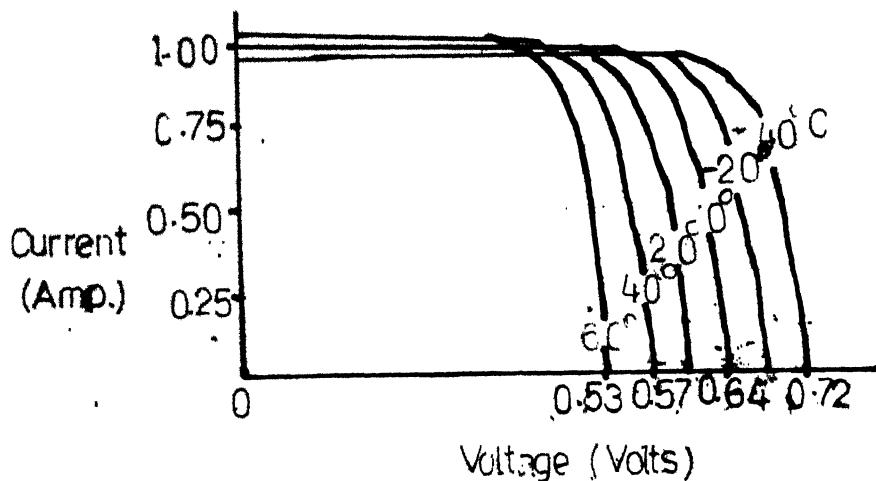
Fig. 2·2·1 b. Characteristics of solar cell with changing temperature

can be sampled either by multiplying the voltage and current readings of PV array together or in a special way by measuring just voltage or current. Several maximum power tracker are reported in literature employing single chip microcomputer [5-6].

The surface orientation of the PV array affects the amount of energy received from the sun and hence PV output power. The amount of direct beam solar energy that a surface receive can be optimized by keeping the surface at right angle to sun's direct radiation at all times. The cost of the energy and the mechanical assembly required to track the sun accurately and consistently each day generally outwieghs the extra energy obtained by doing so, when flate plate solar cell modules without concentration are used [1]. The next alternative is to fix the surface of module so that the sun's angle on the plane is closest to the perpendicular most of the time. In the Northern Hemesphere an area facing due south at a tilt angle that equals to side's latitude would obtain the optimum amount of the entire year. The solar energy over energy can be maximized during winter months by increasing the tilt angle by 11° and in summer months by decreasing the tilt angle by 11°. However tilting a surface up from the

horizontal decreases the diffuse radiation and reflection received from the ground. Therefore for a precise optimum tilt angle the relative amount of the direct diffuse and reflected light must be known. The surface tilt angle need not be too precise because a deviation of as much as 10^0 from optimum tilt angle will produce a decrease in incedent solar energy little more than 5% of maximum [1].

2.2.3 Conversion Efficiency:

Amount of the PV power output of solar cell array depend upon the amount of the solar energy and conversion effeciency of the solar cell. The solar power received directly outside the atmosphere is continuous at a rate of about 1350 watts/m^2 and is known as solar constant. The solar power level received on the earth fluctuates due to rotation of earth at its axis and around the sun. The peak solar power experienced on a horizontal surface near sea level is about 1000 watts/m^2 and is called one sun at which solar cells usually are rated. The conversion effeciency of a solar cell is only about 15%. The theoretical maximum effeciency is about 25%. Major factors responsible for low conversion effenciency are as follows [1-4].

a) The sun light consists of photons having different energies.
The photon having energy less than the band gap energy of
silicon passes straight through crystal with no effect. This
wastes about 24% of solar energy.

b) Since each incident photon having energy more than band gap
energy of silicon is capable of generating one and only one
electron hole pair, hence over energetic photon does
nothing but make the crystal hot. This waste another 32%
of solar energy.

c) Despite of antireflection coating about 3% of incident
energy is lost through reflection. Recombination of electron
hole pair due to impurities in crystal and limited life time,
and absorption of photons away from the depletion layer
causing heat, acounts for another 20% unavoidable losses.

The above mentioned first two factors are inherent with
the silicon solar cell. The latter two factors can be limited
by clever design but can not be eliminated.

A stand alone photovoltaic power system needs some form
of energy storage and/or auxilary power supply to supply the
load demand during night or cloudy day. The general practical
technology for electric so storage is Lead acid batteries which
are ineffecient and expensive. The next alternative is public

utility grid whenever possible. For the application of water pumping instead of electric power, water can be stored in a tank or reservior. This form of storage is most economical and effecient. Moreover solar cells generate power in direct current form which may be converted to ac form by a static inverter. A maximum power tracker may be incorporated in the circuit to ensure maximum possible PV power.

2.3 MOTORS

For a photovoltaic water pumping system, one can employ dc motor, induction motor or synchronous motor. All of them have their own advantages and disadvantages. In the following paragraph these will be discussed.

2.3.1 D.C. Motors:

The most commonly used motor for photovoltaic pumping systems are d.c. motors. The permanent magnet dc motors are prefered due to their high full load and part load effeciency. The permanent magnet dc motors have the full load and part load effeciencies in the range of 78-87% and 66 to 78% for a motor of rating 400W. The full load effeciency of a typical ac induction motor is in the range of 25-65% and that of field wound dc motor would be 65 to 70% for the same power rating.

Despite their high cost, dc drives employing permanent magnet dc motors are cheaper than ac drive or field wound dc drive due to their high effeciency which result in reduction of solar array area [7,8]. All type of dc motors suffer from the disadvantage of brushes and commutation. Generally such machine require new brushes at ininterval of the order of 2000 - 4000 hours and if this is not done some motor can suffer irrepairable damages. Certain dc motors are being offered with claimed brush lives of about 10,000 hours and is to be tested in field conditions. The two alternative schemes are possible for dc drive, either by direct connection of PV array to the dc motor or by connecting a dc to dc converter between PV array and the dc motor. Maximum power can be ensured from the PV array by mannual adjustment of the series/parallel combination in the former case and by incorporating a maximum power tracker circuit in the latter case. However UNDP project report recommend the mannual adjustment. Several approaches for direct connection of the PV array and dc motor has been reported in literature such as graphoanalytic method for series, shunt and sperately excited field wound dc motor [9-10] and analytical analysis of series excited field wound motor [11]. The direct connection of dc motor and PV array requires less number of components hence it is efficient and economical but

suffers from the serious limitation of proper matching of the different components and dependence on the site parameters for good performance. On the other hand one has to sacrifice the effeciency when dc to dc converter with max power tracker is employed. For the best choice a comparative study of both scheme is required.

2.3.2 Induction Motor:

The induction motor offer certain advantages over the dc motor such as low cost, low maintinance due to absence of brushes and commutator, rigid and robust construction but suffers from the disadvantage of low full load and part load efficiency in low power rating. However for the motor ratings greater than 1 KW, the efficiency is comparable with field wound dc motor. Since PV power is in direct current form, an expensive inverter is needed, when ac motors are employed. In low power rating single phase induction motors are used due to their general availability. Permanent capacitor motors are prefered due to their high power factor, which reduces the rms rating of power switches used in the inverter. In low power applications inverters are realized by employing power transistors or MOSFET's using PWM technique at high frequencies. The basic drive scheme may

consists of a PV array, PWM inverter and induction motor.
However maximum power from the p/ PV array can be ensured by
incorporating a maximum power tracker between the inverter
and induction motor. Any suitable scheme of speed control
such as constant v/f ratio, constant flux ʊʋ slip regu-
lation can be employed. There is no published literature on
photovoltaic induction motor pump drive. However some
manufacturers, like 'GRUNDFOS International Denmark' have
designed such drive with 3 phase induction motor, PWM
inverter and submersible pump employing constant v/f ratio
speed control scheme and maximum power tracker with claimed
efficient performance.

2.3.3 Synchronous Motor:

The synchronous motor for pumping applications are
used either as a true synchronous motor where speed is
controlled by an independent oscilator or in self control
mode where pulses for firing of stator inverter are obtained
from the shaft sensors so that speed of rotation of stator
flux is always equal to the speed of rotation of rotor.
Self controlled synchronous motor (SCS) is also known as dc
commutator less motor due to similarity of operation. For
low power applications such as photovoltaic pumping system,

permanent magnet self controlled synchronous motor are prefered due to following advantages [8].

i) If can be operated at near unity power factor. Elemination of reactive power results in minimal size of inverter - motor system.

ii) Load commutation is possible. This make the inverter simple, more efficient and reliable, when thyristors are employed.

Therefore permanent magnet self control synchronous motor seems more attractive than the permanent magnet dc motors. Because these motor do not have slip rings or brushes. However el ctronics gave reliability problems and it is some what less efficient than the better brushed permanent magnet ~~electric~~ $d.c$ motors [7]. For the low power application power transistors and MOSFET's are employed in the inverter to eleminate forced commutation problems. The speed of the drive can be controlled by keeping v/f ratio constant so that the motor runs under ideal flux condition.

2.4 PUMPS

There are two types of pump namely positive displacement and centrifugal. For low heads applications such as small

irregation pumping system, positive displacement pumps seems
inappropriate on efficiency, size and starting consideration.
Therefore a simple single stage centrifugal pump seems to be
best choice. The UNDP project report recommends for the same.
The several approaches have been published in literature to
ensure efficient and stable operation of pump. Author [12]
suggest a graphical approach to operate the pump at its maximum
efficiency with the help of Q-H curves of pump and system.
While author [11] suggest an analytical methods for analysis
and prediction of performance of the pump. Selection of a
centrifugal pump is made so that it fulfills all the requirement
of the systems and its base speed Q-H curve should intersect
the maximum efficiency point in the system Q-H curve. Then
an appropriate drive is selected to match the pumping power
requirements at variable speed.

CHAPTER 3

PROPOSED DRIVE SCHEME

3.1 INTRODUCTION

The water pumping for irrigation purposes is one of
the application of photovoltaic power. Usually time and
amount of PV power matches the water demand of irrigation,
otherwise excess water during summer can be stored in tanks or
reservior for latter use. This storage technique is more
efficient and economical than the battery storage of PV power.
The remote location of pumping systems and high cost of PV
array suggest the use of a drive, which has high efficiency,
high reliability, low cost and needs very little maintenance.
Various drive schemes are possible. Some of them were
discussed in the previous chapter. The permanent magnet dc
motor drive is most efficient but gives maintenance
problems. The ac permanent magnet motor drive overcomes the
problem of maintenance but involves complicated electronics
which may cause problems of reliability. The next alternative
is induction motor drive. The only disadvantage of this
drive is low efficiency specially in small power applications.
For the power level below 500W, single phase induction motors

are preferred due to their easy & availability. These motors
need smaller, less expensive, ~~more reliable~~ and simpler
inverter than poly-phase induction motor due to less number
of components. The main disadvantage of a single phase
induction motor drive is low starting torque. The permanent
capacitor motor is prefered because it is free from the
fractional parts such as centrifugal/ switch or brushes [13].
The efficiency and power factor of permenent capacitor motor
is higher than that of other single-phase motors. Due to
high power factor the reactive power consumption is less, which
results in low RMS current rating of power switches. Moreover,
low starting torque does not pose any problem with the
parabolic loads such as fan or pump loads. Therefore for a
small power PV water pumping system, single phase permanent
capacitor induction motor is one of the best suitable choice.
Such a drive consists of a PV array module, an induction motor
and an inverter with suitable control scheme as shown in
Fig. 3.1.1. In this chapter, these components of the drive
scheme will be discussed.

3.2 PV ARRAY MODULE

The solar cell which converts solar energy directly in
to the electricity is capable to produce 0.6 - 0.8 of peak
watts of power. Usually they are connected in series,

dc/ac converter

PV array
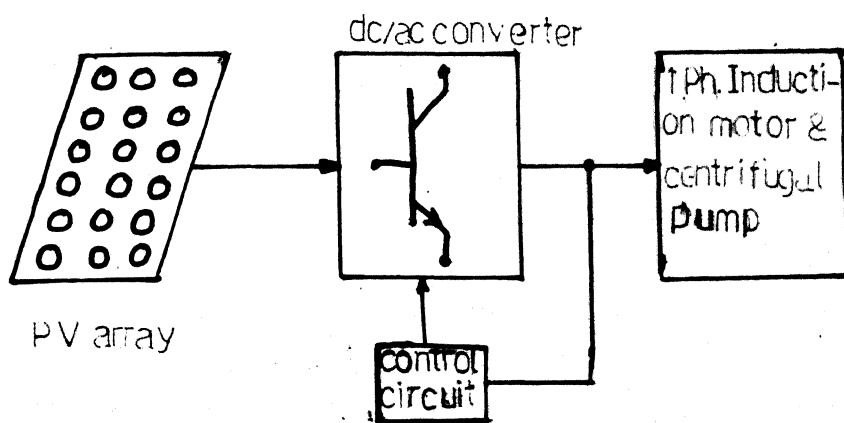
Fig. 3.11   Proposed drive scheme
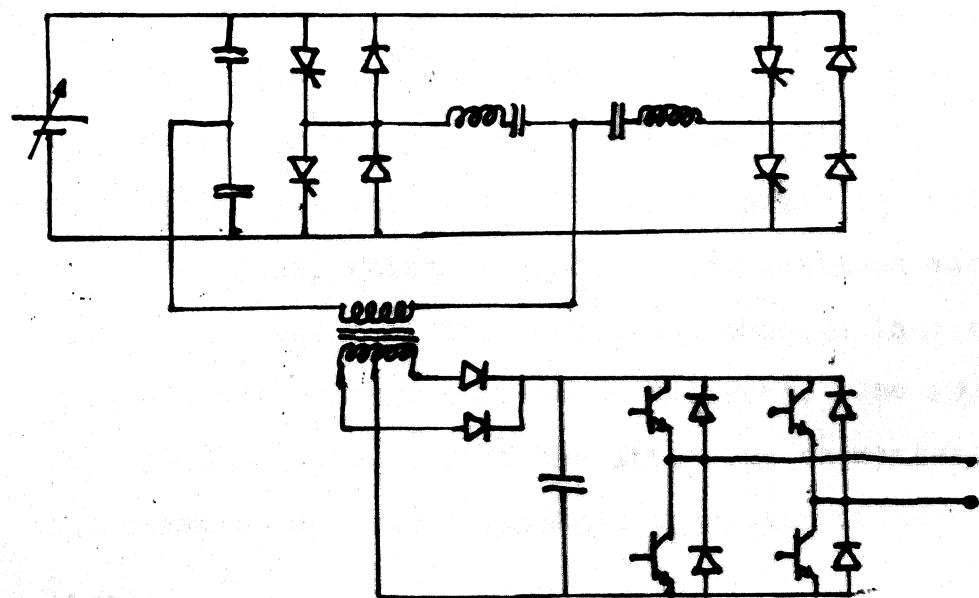
Fig.3.31a High freqency link resonant inverter

parallel or in combination of both to produce the desired input voltage, current. Generally low current high voltage connections are prefered to limit the losses in the load. However a dc voltage greater than 80 volts may present serious electricution hazard and should be avoided. The PV arrays should be mounted on a structure so that they receive optimum solar energy throughout the year and should be protected against the climatic condition of the site.

A PV array module was designed by connecting four solar cell pannels in series. Each pannel contains 36 series connected solar cells to produce 25 watts of peak power. These pannels were mounted on an iron frame facing south. The frame was bolted to a structure so that it makes an angle of 26.44° from the plane, which is equal to the latitude angle of the site. This value of tilt angle was choosen to receive optimum solar energy throughout the year. The PV array module was placed on the roof of the lab. The characteristics of the array at a typical climatic condition is shown in Fig. 3.2.1.

3.3 INVERTER

The photovoltaic induction motor pump drive needs a static inverter to convert available direct current PV power
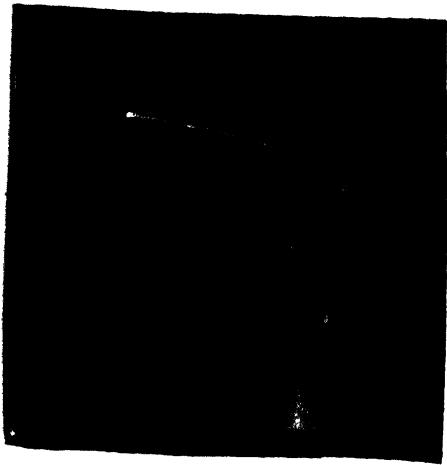
scale :–

    vertical axis –

                  PV current (1·66 A / div.)

      norizontal axis –

                  PV voltage (١٠ V/div;

Fig. 3·2·1   Oscillogram showing characteristics of PV array

into ac power. The static inverter uses power semiconductor switches which are operated at desired frequency to produce alternating current. Such an inverter should produce a sinusoidal current, with low harmonic ~~and the switch~~ should operate ~~at~~ high ~~frequency~~ over a large range of input power and voltages. The reliability of the circuit is also important and can be improved by using least possible number of components. The most commonly used power switches are thyristors (SCR) due to their low cost in high power ratings. But they require ~~an~~ auxilary devices which affects the efficiency and reliability of the inverter. Development of the self extinguishing devices such as Gate Turn Off thyristors (GTO's), Power Transistors and Metal Oxide Field Effect Transistors (MOSFETs) have made it possible to realize reliable forced commutated inverters operated at high frequency. Such inverters have high efficiency, low total harmonic distortion in the output less volume and weight in comparision of conventional thyristor inverters. In the low power and medium frequency applications, power transistors are prefered due to low conduction and switching losses.

The various circuits are reported for use in the photovoltaic application such as high frequency link inverters [5,14]

and high efficiency inverter [6]. The high frequency link
inverter are commonly used in residential photovoltaic power
conditioning system where the $main$ considerations are
less weight, volume and total harmonic distortion in the
output. In such an inverter dc power is converted into high
frequency ac, which is then transformer coupled and converted in
to the required frequency ac through a dc link ac to ac
converter as shown in Fig. 3.3.1. The multistage in the
conversion results is low efficiency, low reliability and
high cost. Author [6] has reported an simple inverter which
converts dc PV voltage into constant frequency ac voltage
without an intermediate dc link, as shown in Fig. 3.2.2 which
results in good efficiency and reliability. An inverter was
designed and fabricated with less number of components than
that of Fig. 3.3.2. The new inverter needs only three power
switches, a flywheeling diode and a central tap transformer.
The circuit of inverter without protection and control
circuit with waveform at different points is shown in
Fig. 3.3.3.

The main power switch MT is operated at high frequency
(20 KHz) employing PWM techniques as a buck converter, which
produces a pulse width modulated high frequency current, I_1
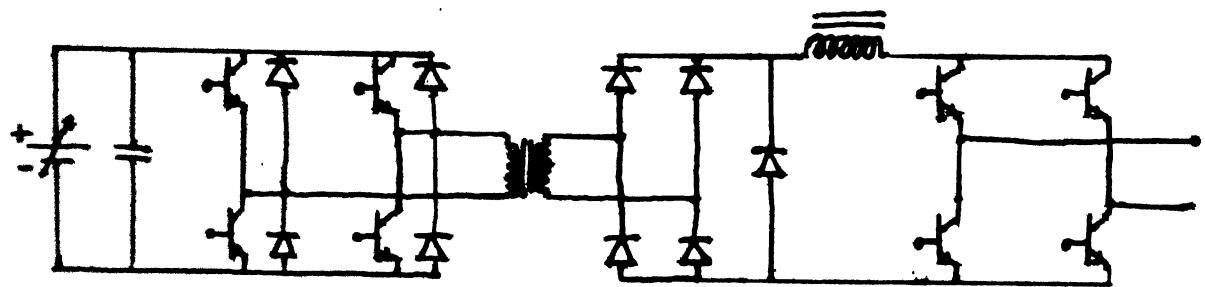
Fig. 3.3.1a   High frequency link inverter
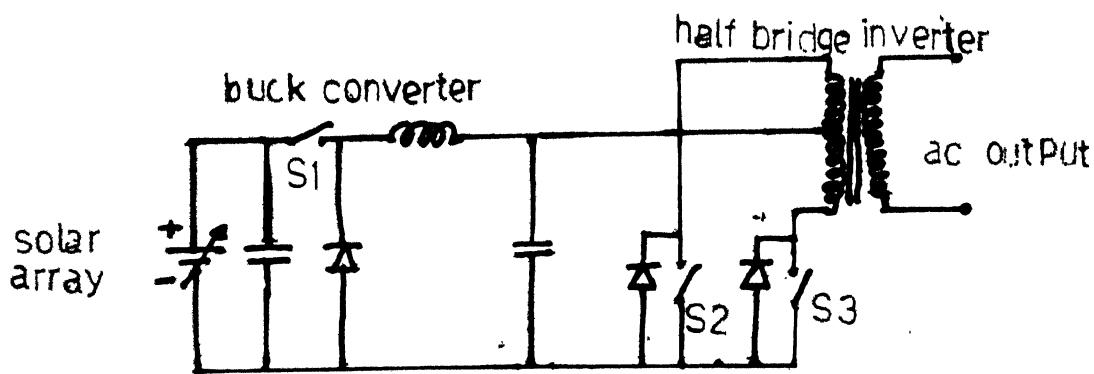
Fig. 3.3.2   Single stage inverter
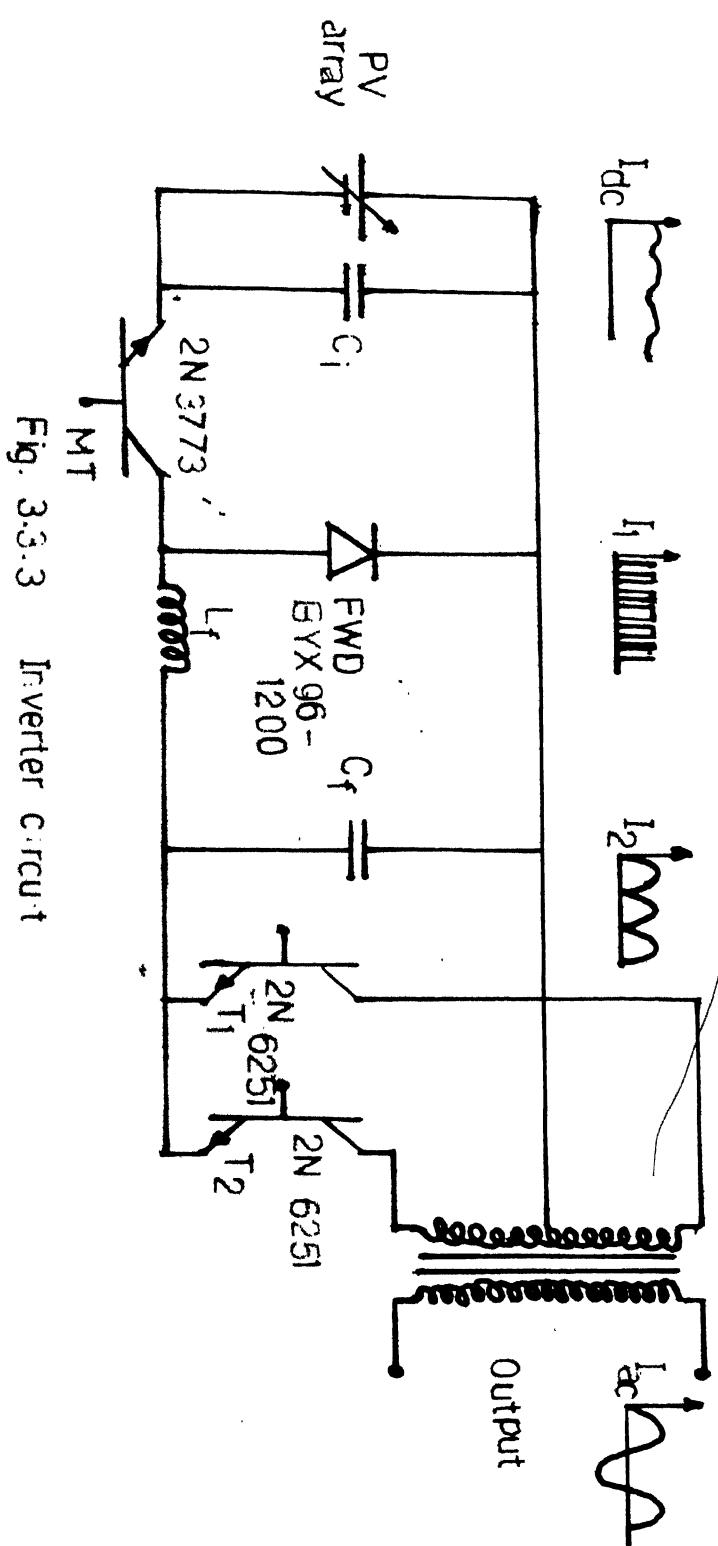
Fig. 3.3.3 Inverter circuit

from the variable PV current I_{dc}. Th*us* *to produce full wave* *high frequency ...* rectified sinusoidal current I_2. The power switches T_1 and T_2 form a half bridge polarity reversing inverter with transformer. The T_1 and T_2 are operated at desired frequency to produce a sinusoidal ac current I_{ac} at the output. The transformer is used to prevent the flow of dc current into the motor and to isolate PV array from the motor. A capacitive filter is connected at the input to limit the ripples in the input voltage and current. A flywheeling diode D_1 is connected to provide an alternative path for the current during the off period of MT.

All three power switches were *rea*lised by power transistors (2N3773). The high frequency (20 KHz) of the chopper was choosen in order to obtain small filtering components [L_f and C_f) and low switching and filtering losses. The low pass filter was realised by a metalized paper capacitor C_f, (15 µF) connected in series with an air core inductor L_f (135 µH). The flywheeling diode uses a fast recovery *doide* (BYX96). The input filter was realized by a parallel combination of metalized paper capacitor (15 µF) with a electrolytic capacitor (2200 µF) to store high frequency *and* low frequency components respectively. A central tap transformer was designed with turn ratio 1:5.5 to produce the desired output voltage level.

3.4 CONTROL SCHEME

The development of the solid state power controllers made it possible to operate the drive in the desired manner. The power output of the drive can be optimized by employing a suitable control scheme. In conventional power fed pump drive, control scheme is responsible for stable and efficient operation of drive, thereby ensuring optimum mechanical output (water). But in case of photovoltaic pump drive, the control scheme should not only be responsible for maximum mechanical output but also the maximum conversion efficiency of PV arrays. An increase in the conversion efficiency reduces the required solar cells arrays area which will result in considerable reduction of overall cost of the drive. The cost of the PV array is more than 80% of the total cost of the drive. In photovoltaic induction motor pump drive, there are two possible control variable, modulation index and frequency ~~of the~~ output of inverter. These variables can be controlled in two ways.

i) select an optimum operating point of the motor characterised by input current and frequency. The motor will absorb a certain power which thus characterised an operating point of photovoltaic array,

ii) operate the PV array at its optimum power which imposes
the supplied power on the motor. This leads to a search
for a frequency of input supply which guarantees an optimum
efficiency from the motor.

Therefore such a drive has two degree of freedom, modu-
lation index is of the inverter, which controls the PV array
operation point at optimum power and frequency of inverter
output f, which optimises motor efficiency. The second control pole
will ensure the optimum power input to the motor only if the
efficiency of theinverter is independent of the load current
which is rarely the case. Therefore first control scheme is
more preferable. This scheme was implemented in proposed
drive.

3.4.1 Control of Modulation Index:

The amount of the photovoltaic output power entirely
depends upon the location of the operating point of the system
on IV characteristics of solar cells array. The operating
point of the system is the intersection point of the IV
characteristic of the array and the load line as shown in
Fig. 3.4.1. Since the IV characteristic of the solar cell
array has a fixed size and shape for a particular values of
temperature and insolation level, the location of the
operating point is mainly decided by the slope of load line.

Therefore amount of the output power of a solar cells array
can be controlled by changing the slope of load line and
hence can be maximised by adjusting the slope of load line so
that operating point of the system concides maximum power
point of the PV array. The slope of load line depends upon
voltage and current level of the load (I/V) and hence can be
controlled by changing the modulation index of the inverter.

Thus proper adjustment of the modulation index can ensure
the maximum output power from a PV array. This can be done by
sampling the output power of array and changing the modulation
index 'm' of the inverter until the power is maximised. The
power output of the PV array can be sampled simply by
multiplying the voltage and current reading together. This
will involve a large number of multiplication and sensing of
both voltage and current, which need a microcomputer. The
several maximum power tracker are reported in the literature
[5,6] for the residential power conditioning system which
work on the above principle and use a single chip micro-
computer. However, for the photovoltaic pump drive which
is to be located in remote sites the use of microcomputer
is risky and reliable operation of such a system is doubtfull
in field conditions.

The power output of the PV array can also be maximised by maximising the ~~first~~ voltage or current input to the load provided I-V characteristic of the load does not reaches a maximum. In other words load line does not have a negative slope region which can be true in case of induction pump drive if proper speed control scheme is employed. In the proposed scheme the input voltage to the motor is sampled regularly and modulation index is varied. If the input voltage to the motor increased or remain same the modulation index is varied in the same direction otherwise direction of change in the modulation index is reversed. Thus the operating point of the system fluctuates around the maximum power point of the PV array. The actual circuit used and its operation will be discussed in the next chapter.

3.4.2 Control of the Frequency:

The control of the modulation index will ensure the optimum voltage input to the motor. Since the mechanical output power of pump drive is proportional to the speed, a suitable speed control scheme should be employed which adjust the speed of the drive for corresponding change in the input voltage. Usually speed of the single phase permanent capacitor motor is controlled by reducing the strength

of the air gap magnetic flux or the synchronous speed of the
motor. The strength of the magnetic flux can be controlled
by changing the stator voltage at constant frequency, while
synchronous speed of the motor is controlled by varying the
frequency of the stator supply.

The speed-torque characteristic of a single phase
permanent capacitor motor for different stator voltage is
shown in Fig. 3.4.2 a. This method of speed control is most
suitable for the parabolic load such as pump because of *limited*
~~large~~ range of speed control. The disadvantage of this
method is low efficiency at low-speed range. Moreover the
input current of the motor increases with decrease in the
speed upto about 33% slip and then start decreasing. There-
fore the load line will have a negative slope if the slip
of motor is more than 33% which is undesirable for the
proposed maximum power tracking scheme.

The other way of speed control is by controling the
input frequency. The voltage is to ~~the~~ frequency ~~is in~~ *ratio*
kept ~~depth~~ constant to ensure the operation of motor at ideal
flux condition. In poly-phase induction motor the constant
maximum torque is produced at all speeds. But in the single
phase induction motor, this is not the case. The maximum
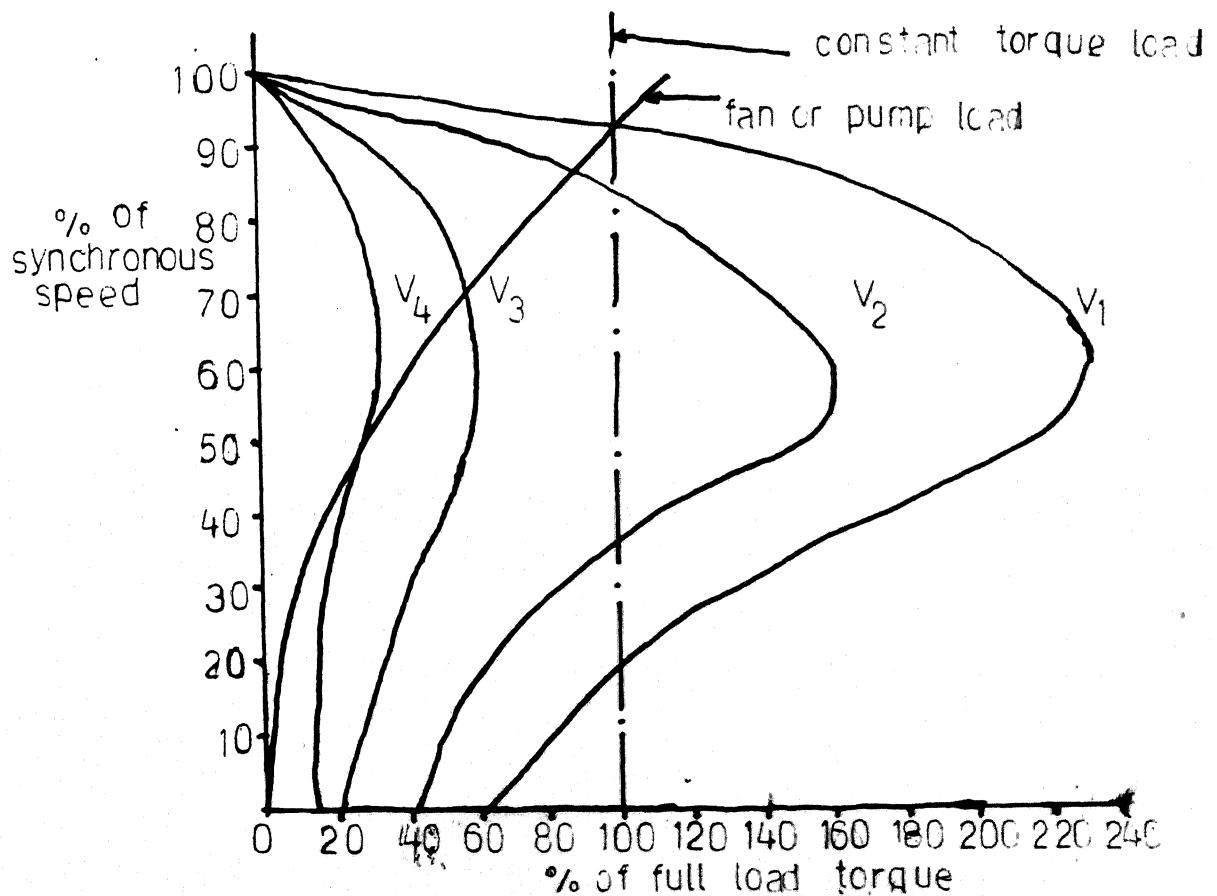
Fig. 3.4.2a Speed-torque characteristics of permanent capacitor I.M. with variable Voltage
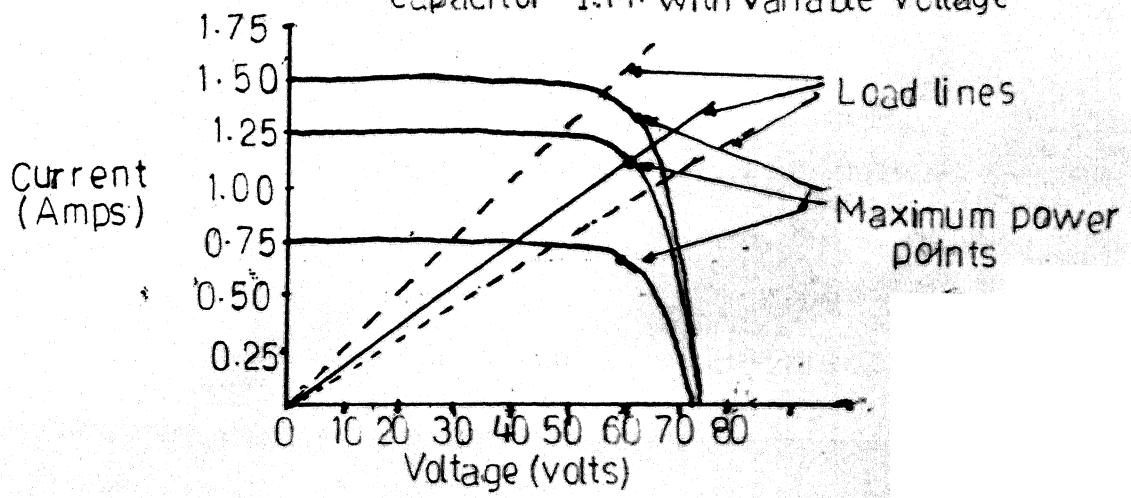
Fig. 3.4.1 P.V. array characteristics & load line

torque produced by the motor decreases with the decrease in the speed inspite of constant V/F ratio as shown in Fig. 3.4.2b. The reason is quite simple. The strength of the cross magnetic *Flux* ~~form~~ in the single phase induction motor depends upon the speed voltage induced in the rotor and decreases with the speed. The reduction in the torque at low speed is favourable for pump *and* ~~to~~ fan loads. This method of speed control is more efficient than the former one. The efficiency of drive can be improved further by varying the V/F ratio so that the maximum torque produced by the motor is slightly more than the load torque at all speeds.

In this project both of the speed control schemes were implemented.
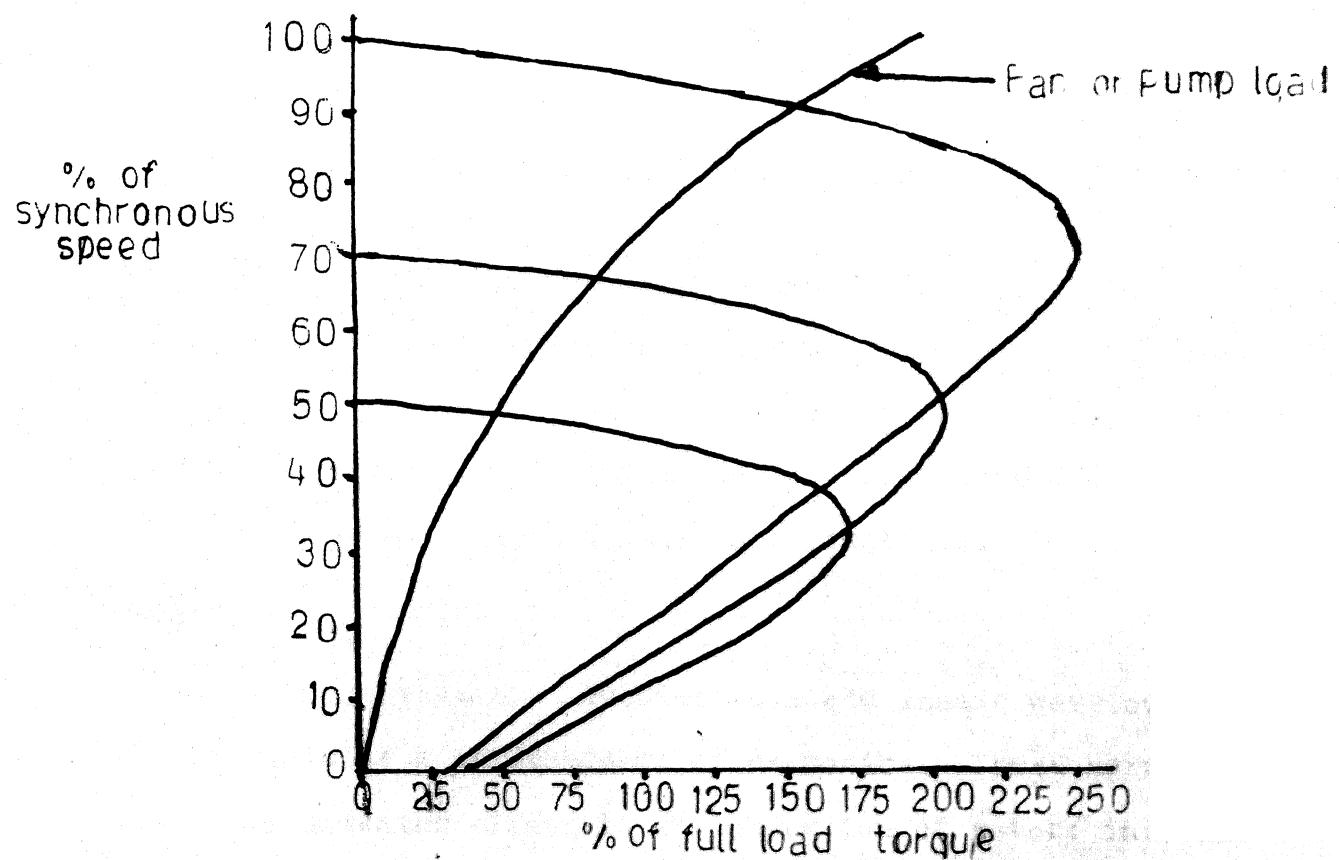
Fig. 3.42b Speed-torque characteristics of permanent capacitor I.M. with constant V/f ratio

CHAPTER 4

CONTROL AND PROTECTION CIRCUITS

The design and operation of the control and protection
circuits will be discussed in this chapter. The control
circuit consists of firing circuit, base drive circuit, maximum
power tracker circuit and voltage controlled oscillator
(Fig. 4.1), while snubbers ~~were~~ are provided to protect the power
switch from secondary breakdown. Since the PV array regulates
its voltage and current, no protection is provided for over
current or over voltage to the power switches.

4.1 FIRING CIRCUIT

Normally static inverters produce square wave output,
which contains a large number of harmonics. These harmonics
have two unwanted effects on the operation of motor, increase
in heating and torque pulsation due to distortion in the air
gap flux. Therefore, it is desirable that harmonic components
of the waveform should be minimum. The harmonic content of
the waveform can be controlled by employing pulse width modu-
lation techniques. There are several PWM techniques such as
sinusoidal PWM modulation with uniform sampling (SPWM) optimal
pWM and harmonic elemination. For the transistor inverters
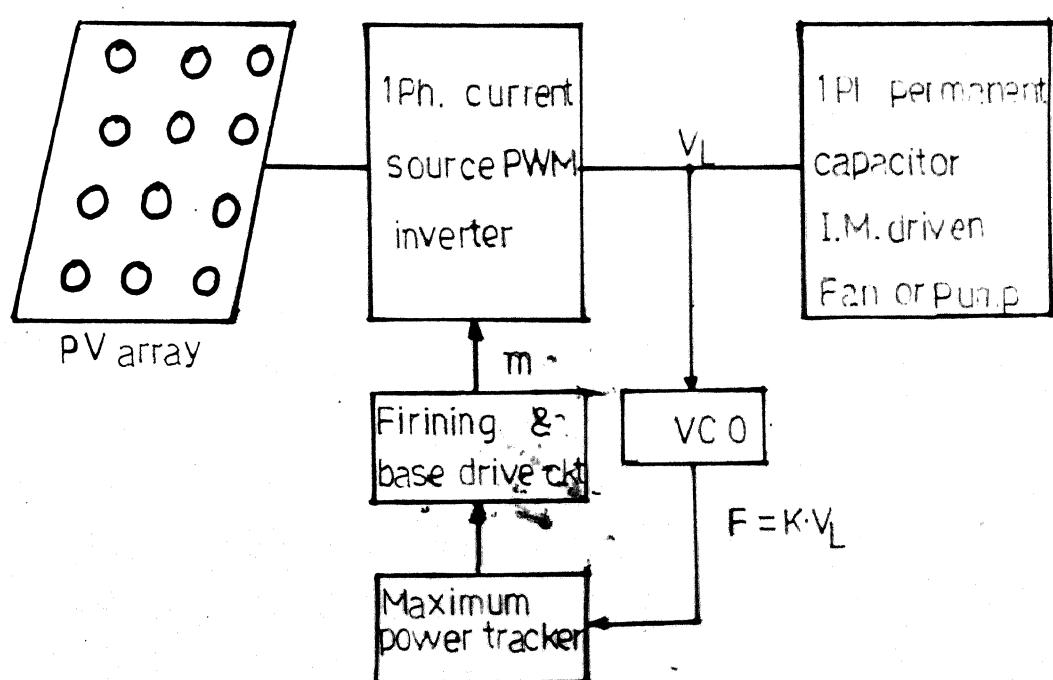
Fig. 4.1   PV Induction motor pump drive
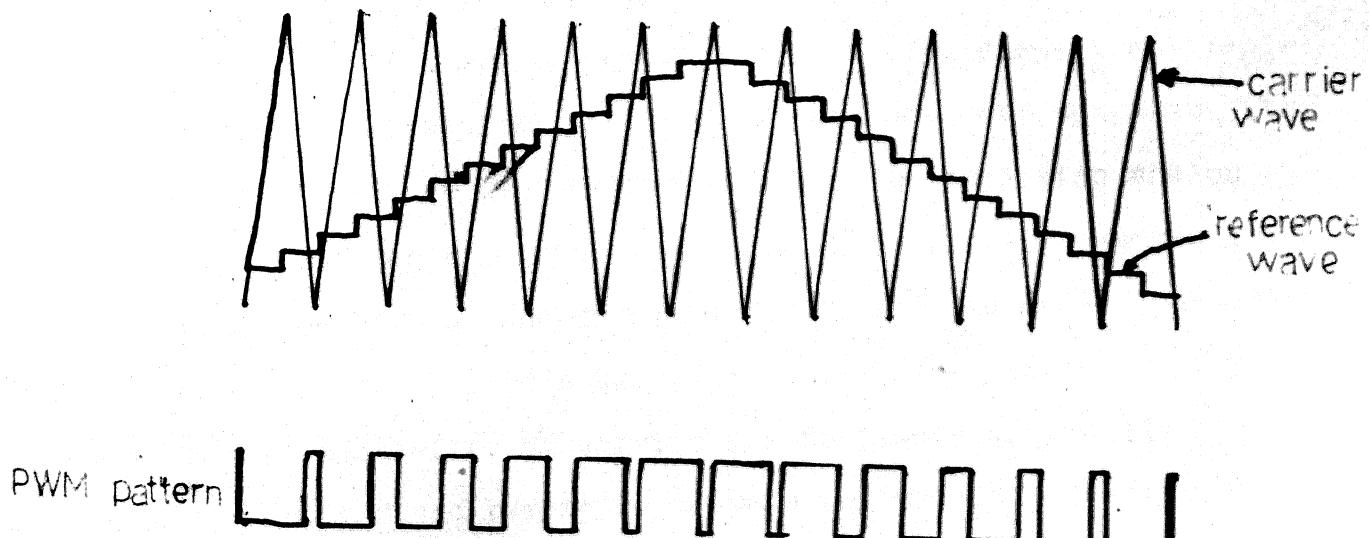
Fig. 4.1.1   PWM Pattern generation

SPWM is most suitable and can be implemented either by natural comparision. In natural comparision a sine wave of variable frequency and amplitude is compared with the triangular wave of carrier frequency. Since it is difficult to generate a sine wave of variable frequency and amplitude, the author of reference [7] have used trapezoidal reference wave instead of the sinusoidal. The switching instant can be calculated on main frame computer and can be stored in EPROM. However for high carrier frequency a large storage area will be required, which is not economical.

In the proposed drive scheme a stepped triangular reference wave of variable frequency and amplitude was used because it is easy to generate such a wave shape than trapezoidal or sinusoidal. This reference wave was compared with fixed frequency (20 KHz) triangular wave employing analog techniquea as shown in Fig. 4.1.1. The circuit was realised with the help of the counters and digital to analog converter (DAC). The amplitude and frequency of the reference wave can be controlled by varying the frequency of the clock for the counter and reference voltage of the DAC1 respectively. The clock is provided either by an independent oscillator, whose frequency can be controlled or from the output of a VCO.

The independent oscilator is realized by NE566 chip. The
output frequency is kept 1024 times the desired output
frequency. The magnitude of the reference voltage to the DAC
is provided from the output of maximum power tracker circuit.
The complete circuit is shown in Fig. 4.1.2 and its wave —
form is Fig. 4.1.3.

A 8 bit up down counter, which uses two cascaded 74191
chips, counts the input clock continuously and produces a
high pulse CO at max./min. pin whenever its count content
becomes OO or FF. The signal CO triggers a positive edge
monore MV [1/2 74LS221] to produce a short duration pulse
(2 μsec). This pulse toggels a JK flipflop [1/2 7476] to
produce a signal U. The signal U is connected to the up down
pin of the counter which makes the counter to count up and
down when its content becomes OO and HH respectively. The
counts output of the counter is connected to digital to analog
converter [ADC 7523JN]. The output of DAC is level shifted
and amplified to produce the stepped triangular reference
wave RW. The fixed frequency triangular wave is generated by
using a NE566 timer. The output of timer is level shifted and
amplified to produce carrier wave CW. These waves RW and CW
are compared by using a high speed comparator [LM361], whose

Fig. 4.1.2   Firing circuit

max/min of
counter   co

output of mono
               M1

Up/down signal
to counter   U

Pulses to T1

Pulses to T2

Reference wave
              RW

Carrier wave
  CW

Pulses to MT
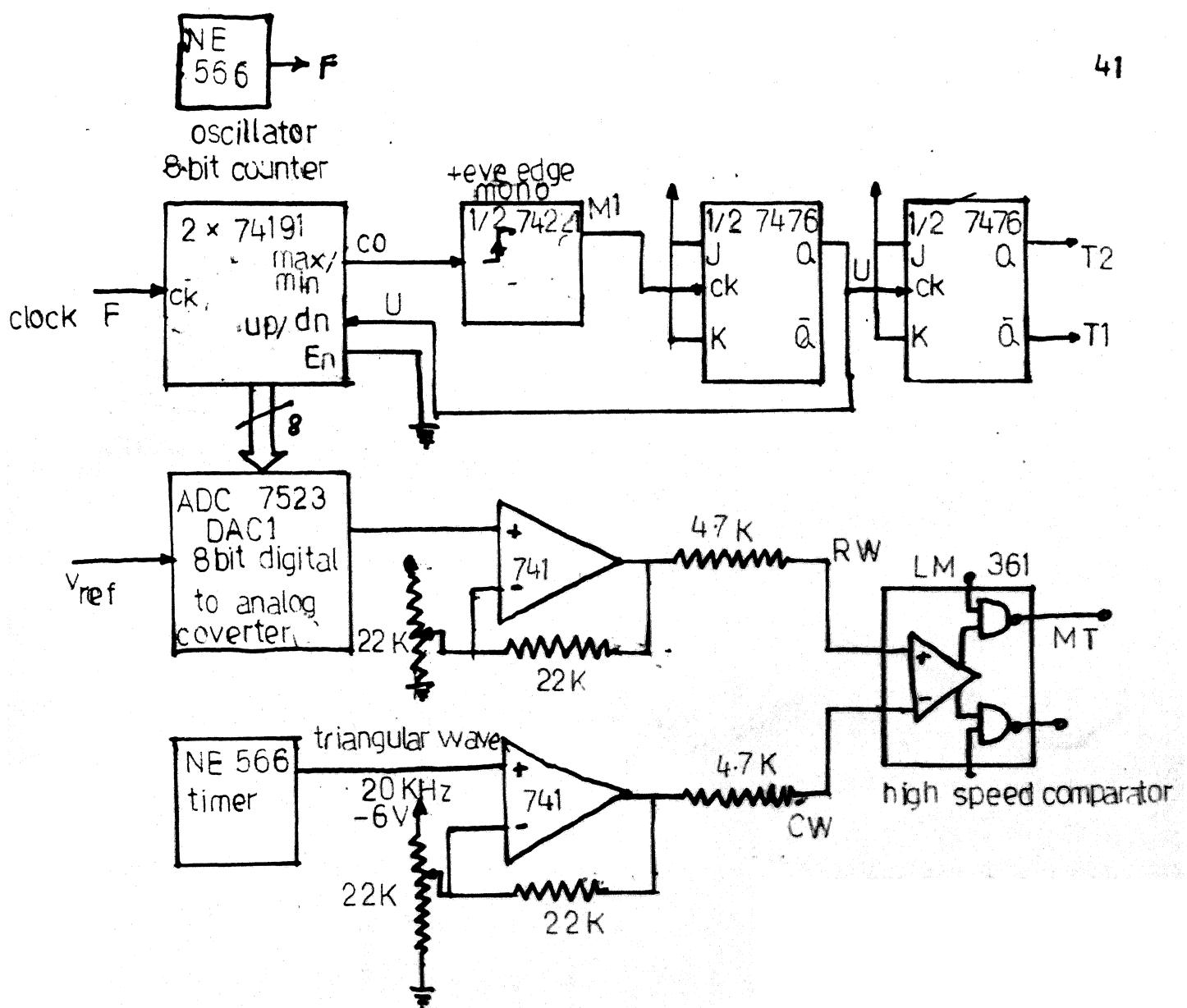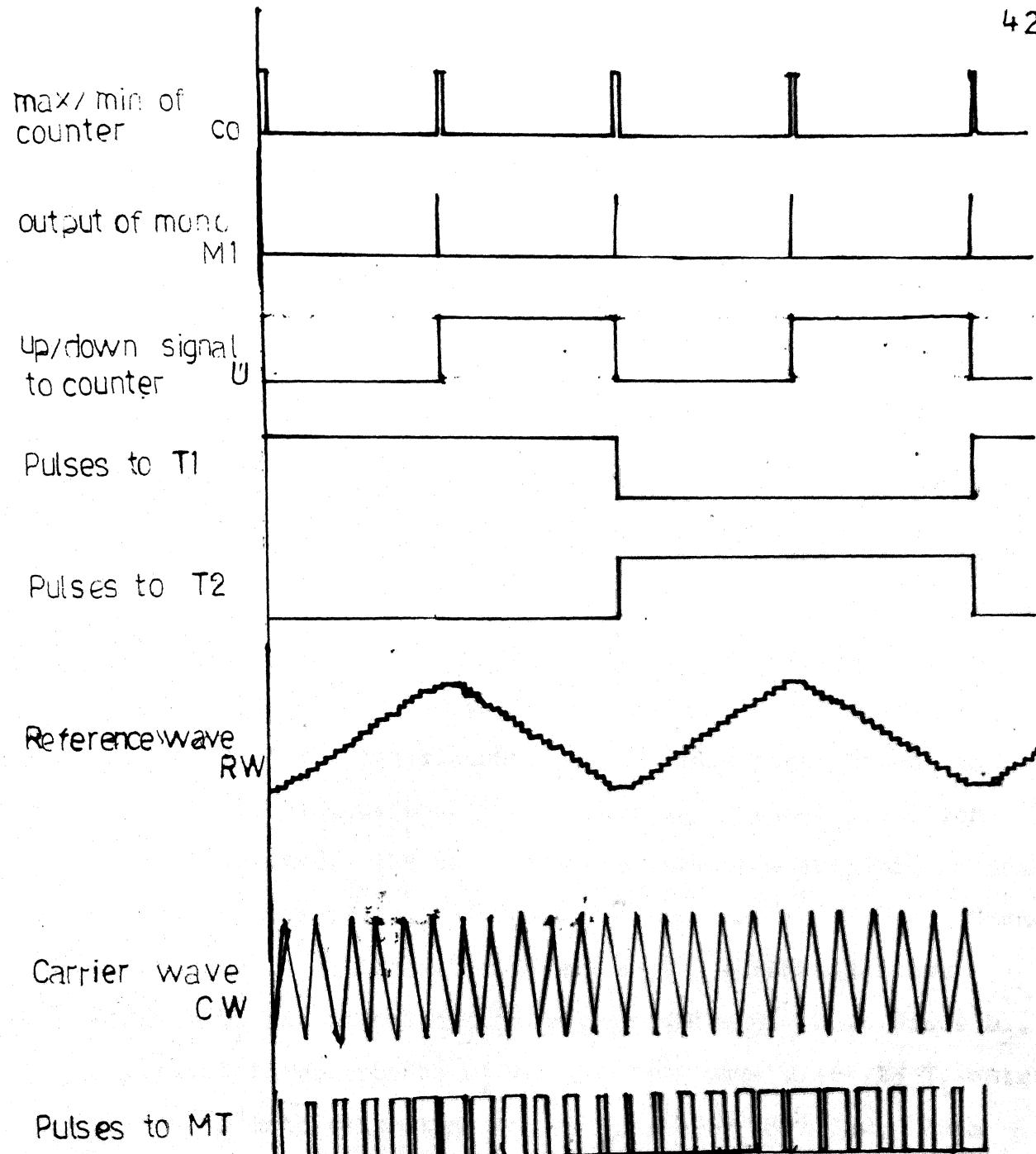
Fig. 4.1.3   Waveforms at different points of firining ckt.

output is the required PWM pattern. The signal toggels an
another JK FF [1/2 7476] to produce the complemented square
waves. The frequency of these waves is half of the frequency
of reference wave and used to trigger power transistor T_1
and T_2.

4.2 BASE DRIVE

The base drive circuit is used to amplify the switching
pulses and to reduce the switching time and conduction losses.
The firing circuit should also be protected from the high
speed large voltage and current transient in the power circuit
by isolating the two circuits [16]. Since power transistor
requires continuous base drive, pulse transformer isolation
can not be used. The opto isolator are used for this purpose,
such an optoisolator 4370/5082 is shown in Fig. 4.2.1. When-
ever there is a high pulse at the input, a current flows
through D_1 and it emits light which strike to photo diode D_2.
A current flows through D_1 and provides base drive to T_1 which
drives T_2 into saturation and hence output goes low. When
input signal is low T_2 will be in cut off and output will be
high. The optoisolator needs an isolated power supply to
isolated the output from the input. Such a power supply was
designed as shown in Fig. 4.2.2.

5 V

510

D₁

D₂

T₁

T₂

6 V

1K

10 K

Output signal

ut signal

4370/ 5082
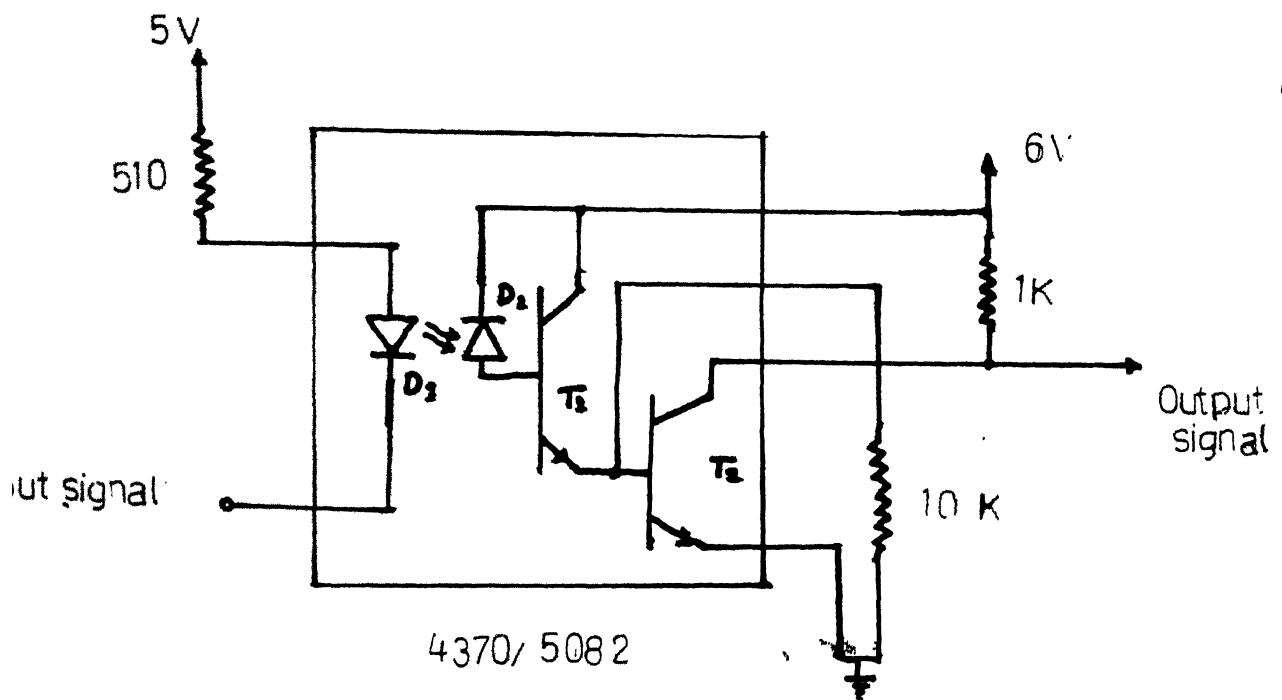
Fig. 4.2.1   Optical   isolator

6 V

+ve

BY125

2200 μF

220 Volt
a c

0 V

Gnd

2200 μF

6 V

-ve
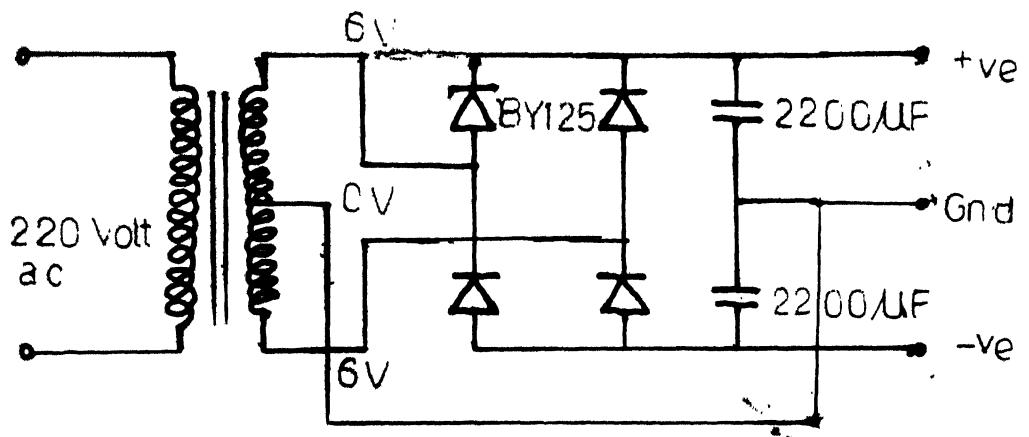
Fig. 4.2.2   Isolated power supply

A simple base drive circuit was realised as shown in
Fig. 4.2.3. Input signal is isolated and amplified by
transistors Q_1 and Q_2 so that it can drive transistor pair
Q_3-Q_4 into saturation. To reduce the storage time and hence
the switching time and losses, transistor, Q_4 produces
the negative base drive when power transistor is to be off.
An alternative path for the negative base drive is provided
by connecting zenor diodes at the output after the storage
time, which protects the base emiter junction from the
avalanche breakdown. The storage time can be reduced further
by controling the depth of the saturation of the PT. This
is obtained by connecting diode D_1. As the saturation level
of PT increases, D_1 becomes forward biased and by passes
certain portion of the base drive of Q_3 and Q_4 to collector
of the PT and hence reduces the base drive to the PT and thus
reduces the saturation level. The capacitors, in the collectors
circuits of Q_3 and Q_4 are connected to provide high initial
base drive of about 2.5 μsec.

4.3 VOLTAGE CONTROL LED OSCILLATOR

The circuit of VCO is shown in Fig. 4.3.1. The input
voltage to the motor is stepped down, rectified and filtered
to obtain a dc voltage V_1. The dc voltage V_1 is proportional
to the motor terminal voltage and connected to control voltage
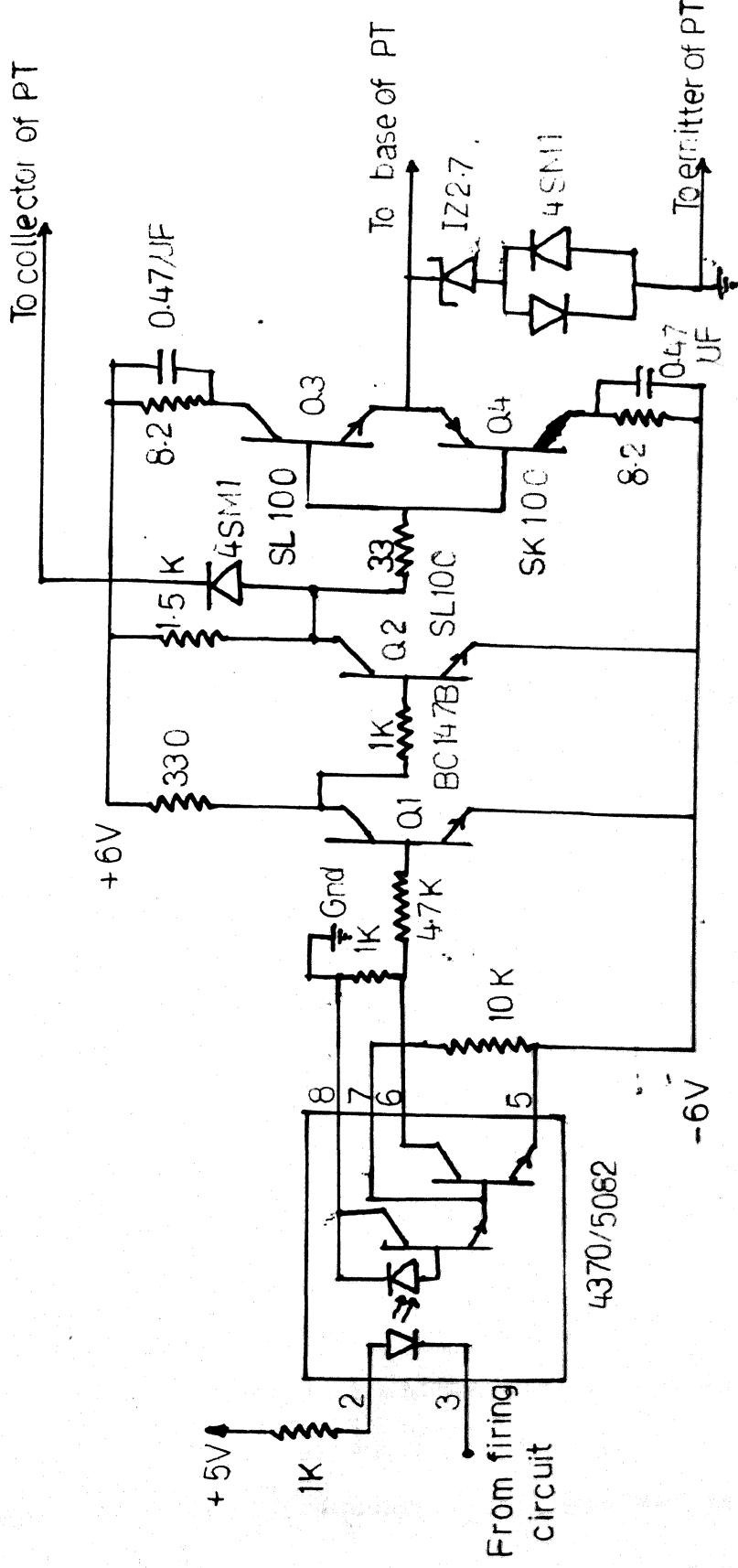
Fig. 4.2.3   Base drive circuit
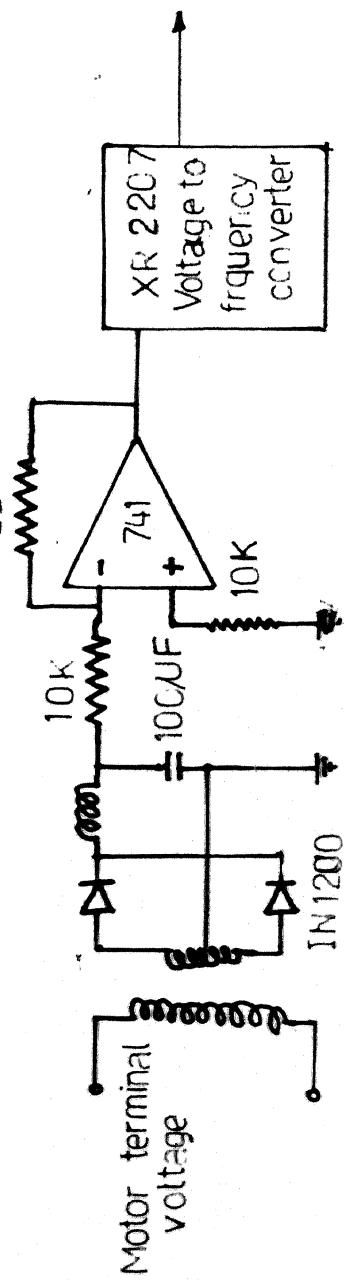
Fig. 4.3.1   VCO Circuit

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pin of a voltage to frequency converter chip [XR2207]. The
timing components of XR2207 chip is selected to maintain
a constant ratio of its output frequency to motor terminal
voltage so that the ratio of the motor terminal voltage and
inverter frequency is maintained at rated value. The
rated V/F ratio of motor is 4.4.

4.4 MAXIMUM POWER TRACKER CIRCUIT

A simple maximum power tracker is proposed which
maximises the input voltage to the motor by controling the
modulation index of the inverter. The input voltage to the
motor is continuously monitored and converted in to frequency
by using a VCO. The output frequency of VCO is proportional
to the motor terminal voltage (VL). This frequency F_1 is
measured and is stored. Then the modulation index of the
inverter is either incremented or decremented depending upon
the previous condition. The variation in modulation index
will change the terminal voltage of the motor and hence
output frequency of the VCO will change. An adequate time
is provided to settle the power transient. The new output
frequency of VCO F_2 is measured and compared with the previous
value of frequency F_1. There are three possibilities.

a) $F_2 > F_1$ i.e. motor terminal voltage has increased

b) $F_2 = F_1$ i.e. the terminal voltage of the motor remains the same

c) $F_2 < F_1$ i.e. the terminal voltage of the motor has decreased.

In cases (a) and (b), since the motor terminal voltage is either increased or remain the same, the change in the value of modulation index is considered in right direction and it will be maintained in the next cycle. While in case (c), the terminal voltage is decreased. Therefore change in modulation is considered in the wrong direction, therefore in the next cycle, the direction of the change in modulation index is reversed. The circuit is realised using a digital logic circuit and is shown in Fig. 2.4.1.

The base signal to the power switch T_1/T_2 is used to toggel a JK flipflop J_1 [$1/2$, 7476] which produces a signal A at its Q output. The signal A toggels a JK flipflop J_2 [$1/2$, 7476] and produces UD and $\overline{UD}$. The signal $\overline{UD}$ is connected to the up/down pin of the 8 bit counter C_1 (2x74191). Therefore mode of the counting of counter C_1 changes up and down for every two cycles of the motor terminal voltage of A +Ve edge
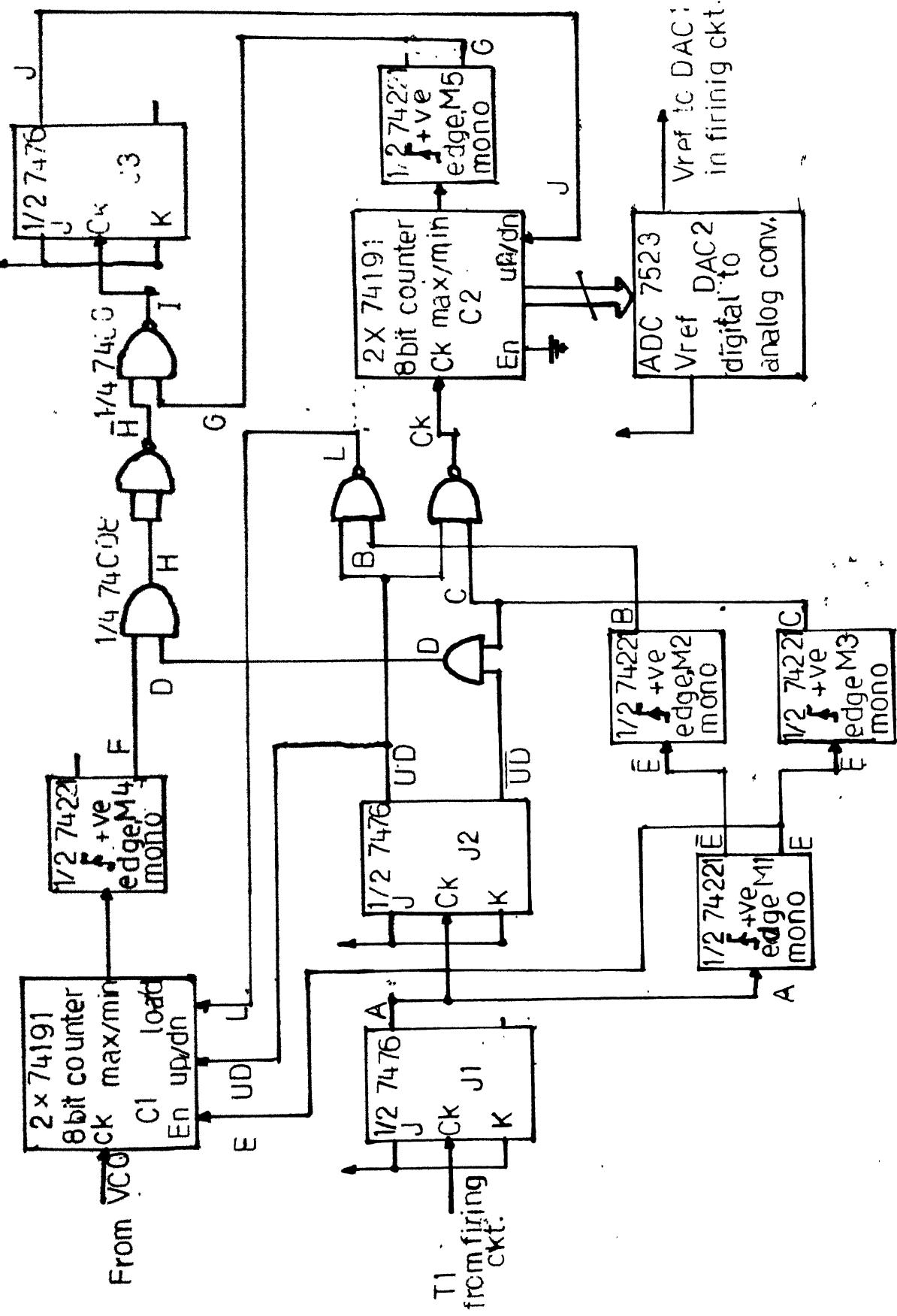
Fig. 4.4.1 Maximum power tracker circuit

mono MV M_1 [1/2, 74LS221] is used to produce a low pulse
. of 3.8 msec duration at the rising edge of the signal A
and is connected to the enable pin of the counter C_1. This
enables the counter C_1 to count up and down alternately
for a duration of 3.8 msec. The signal L and E trigger
+Ve edge mono MV M_2 and M_3 [74LS221] to produce positive
pulses B and I of 0.75 and 1.5 μsec duration respectively.
The pulse B is Nanded with signal UD to produce a low devel
load pulse for counter C_1 so that the counter is loaded with
word FF before it start count down. The clock to the counter
C_1 is provided by the output of the VCO. The output frequency
of which [VCO] is proportional to the terminal voltage of the
motor. The pulse C is Nanded with UD signal to produce a
clock pulse to the counter C_2 (2x74191) whenever counter C_1
stops counting down. The +Ve edge mono M_4 (1/2 74LS221)
produces a 3.8 msec low level pulse F at the rising edge of
ripple clock output of the counter C_1. The pulse C is
Anded with signal $\overline{UD}$ to produce a positive pulse of 1.5 μsec
whenever counter C_1 stops up counting. The pulses D and F
are Anded together and produce a positive pulse H whenever
the counts output of counter C_1 in up counting is Less than
that in down counting. The max./min. output of counter C_2
triggers a +Ve edge Mono MV M5 [1/2 74LS221], which produces a

negative pulses G of 1.5 μsec. The pulses G and $\bar{H}$ are Nanded

together and produce a signal I which toggels a JK flipflop

J_3. The output of J_3 is connected to the Up-down pin of the

counter C_2. Therefore mode of counting of the counter $C2$

changes whenever counts output of counter C_1 in up counting is

less more than that of down counting or the count output of counter

C_2 becomes FF or 00. The counts output of counter C_2 are

connected to a digital to analog converter DAC2 [ADC 7523],

which produces an analog signal V_{ref}. The signal V_{ref} is

connected to DAC1 in firing circuit. The wave forms are shown

in Fig. 4.4.2.

The cycle of the operation begins with loading a word

n into counter C_1. Than counter C_1 starts counting down the

output frequency of the VCO for a period of 3.8 msec. At the

end of this counting period a clock pulse is released to

counter C2. The content of the counter is either incremented

or decremented depending upon the counting mode of counter C_2.

This will result in corresponding change of the V_{ref} signal to

DAC1 in firing circuit and hence modulation index will be

changed. The circuit remains idle for rest of the two cycles

of the terminal voltage of the motor to settle the power

transient. Than the counter C_1 starts counting down up the output

Fig. 4.4.2   Waveforms of maximum power tracker circuit

frequency of the VCO. If the output frequency of the $\overset{\lor}{\not{p}}$CO
is either increased or remains the same then counter will
produce a pulse at its ripple clock output which is used to
block the pulse to, JK flipflop J_3 and the cycle will be
repeated. On the other hand if the output frequency of VCO
is decreased no ripple clock pulse will produce. Then
a pulse will be realsed to JK flipflop J_3 which will reverse
the mode of counting of counter C_2 and thereby direction of
change in the modulation, and the cycle will be repeated.

4.5 PROT CTION CIRCUIT

The power switches used in the inverter circuit must
protected against switching transient otherwise device
may damage due to secondary breakdown [16]. Usually the
polarised snubber circuits are used for this purpose. The
protection circuits limits the rate of rise of current and
the voltage within the prescribed limit at turn on and turn
off of the switch. The snubber circuits are designed so that
the power switch always operates within the safe operating
area [SOA] prescribed by manufacturers and thus keeps the
device heat dessipiation low. The authors of references
[17 and 18] have reported methods of calculation of the

snubbers circuit components in order to reduce losses in the device as well as the total switching loss. The inverter circuit with all protection circuits is shown in Fig. 4.5.1.

4.5.1 Turn on Snubber Circuit:

The turn on snubber circuit is connected only with main transistor due to its high frequency of operation. The circuit consists a small inductance and a diode-resistance network as shown in Fig. 4.5.1. The inductance induces voltages equal to and of opposite polarity of the input voltage when the main transistor current begins to rise, thereby collapsing the collector emitter voltage to its saturation level. By assuming that the collector current rises linearly during the time, the value of inductance can be calculated as follows:

$$V_{in} = \frac{L \cdot I}{T_r}$$

or
$$L = \frac{V_{in} \cdot T_r}{I}$$

The network inductance is charged exponentially during the transistor turn off time by the voltage drop across the network resistance. The network resistance is selected to provide the shortest changing time interval consistent with
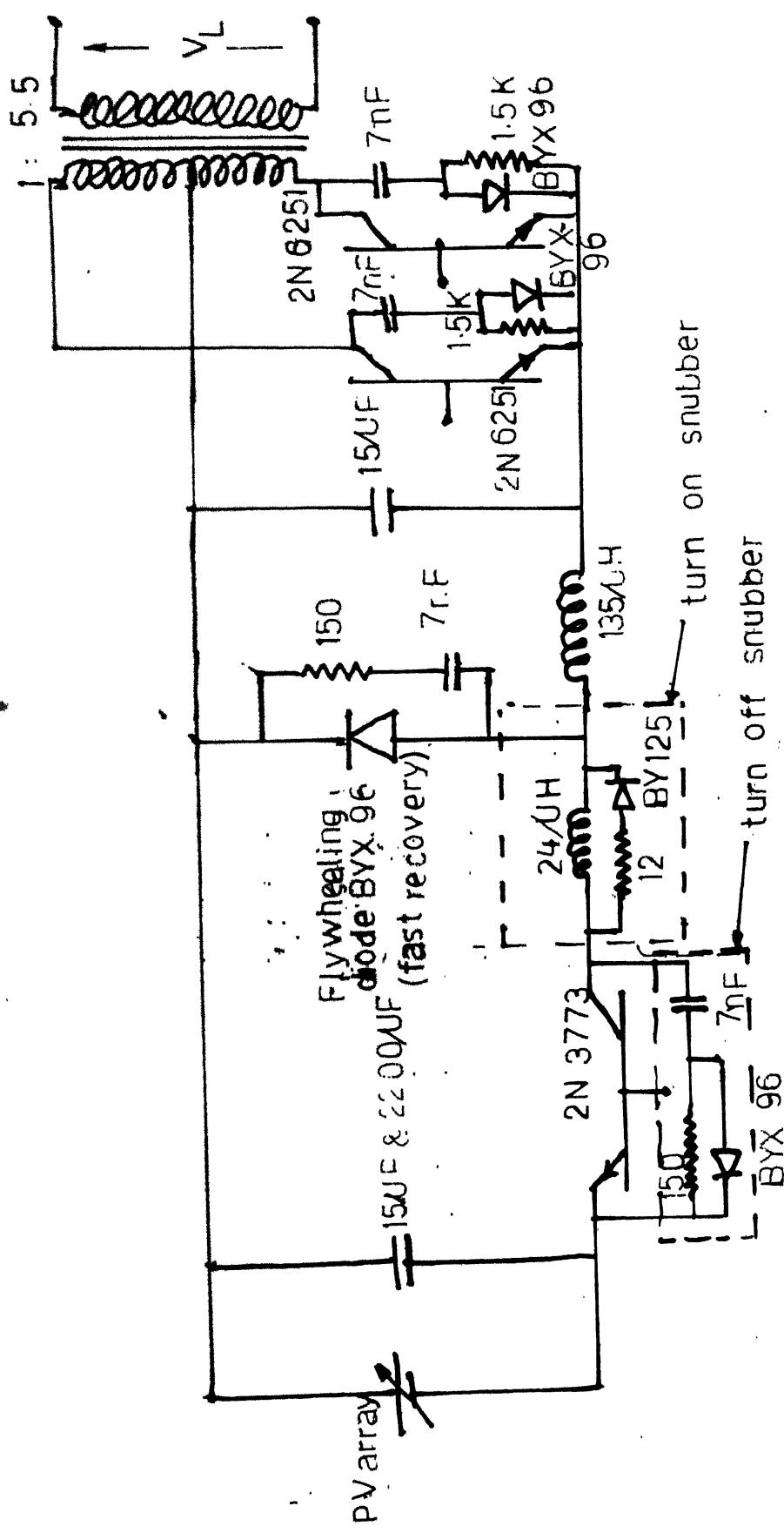
Fig. 4.5.1 Inverter circuit with snubbers

extra burden placed on the transistor by the charging voltage, which appears in series with it at turn off. An inductance of 24 μH and a resistance of 12 Ohms ~~were~~ are selected for the inverter ratings ~~given in Appendix B.~~ of 2 Amp & 60 volts

4.5.2 Turn off Snubber Circuit:

A normal diode-resistance-capacitor network is used as a snubber during turn off. At turn off, the capacitor charges at a very fast rate through a diode and thus limits the rate of rise of the voltage. At turn on it discharges through a resistance to limit the discharge current. By assuming that during turn-off time T_f the collector voltage rises linearly from saturation voltage to input supply voltage. The value of capacitor C can be calculated as

$$V = \frac{1}{C} \int I \, dt = \frac{1}{C} \int_{0}^{T_f} \frac{I \, t}{T_f} \, dt = \frac{1}{C} \frac{I}{T_f} \left[\frac{t^2}{2} \right]_{0}^{T_f} = \frac{1}{C} \frac{I \, T_f}{2}$$

or

$$C = \frac{I \, T_f}{2V}$$

where $V = V_{in}$ + voltage drop across the network resistance.

The network resistance is selected to provide the shortest charging time interval consistent with the extra burden placed on the transistor by the discharge current

at turn on. A capacitor of 7 μF and resistance of 250 Ohms are
selected for main transistor's snubber. However since T_1
and T_2 operate at a low frequency there is a large time
interval available for changing of capacitor therefore
larger resistance can be used to limit the discharge current.
A network of 7 μF capacitors and 1.5K resistance with a
fast recovery diode are used for transistors T_1 and T_2.

4.6 EXPERIMENTAL SET UP

The complete control circuit was fabricated on a single
PCB as shown in Fig. 4.6.1 and was fitted with power circuit
of inverter in a proper metal assembly. Since induction
motor and centrifugal pump were not available in the required
power rating, a pedstall fan of 60W was used. Two DPDT
switches and two potentio meter were fitted at the front pannel
of the inverter assembly. By the help of switches the modu-
lation index and frequency of inverter can be varied either
in close loop or in open loop by mannual adjustment. The
following alternative operations are possible.

a) Modulation index and inverter frequency in open loop:

The level of the input voltage and power to the motor
as well as inverter frequency can be adjusted to any desired
value by setting the positions of potentio-meter, which are
fitted on the front pannel of inverter.
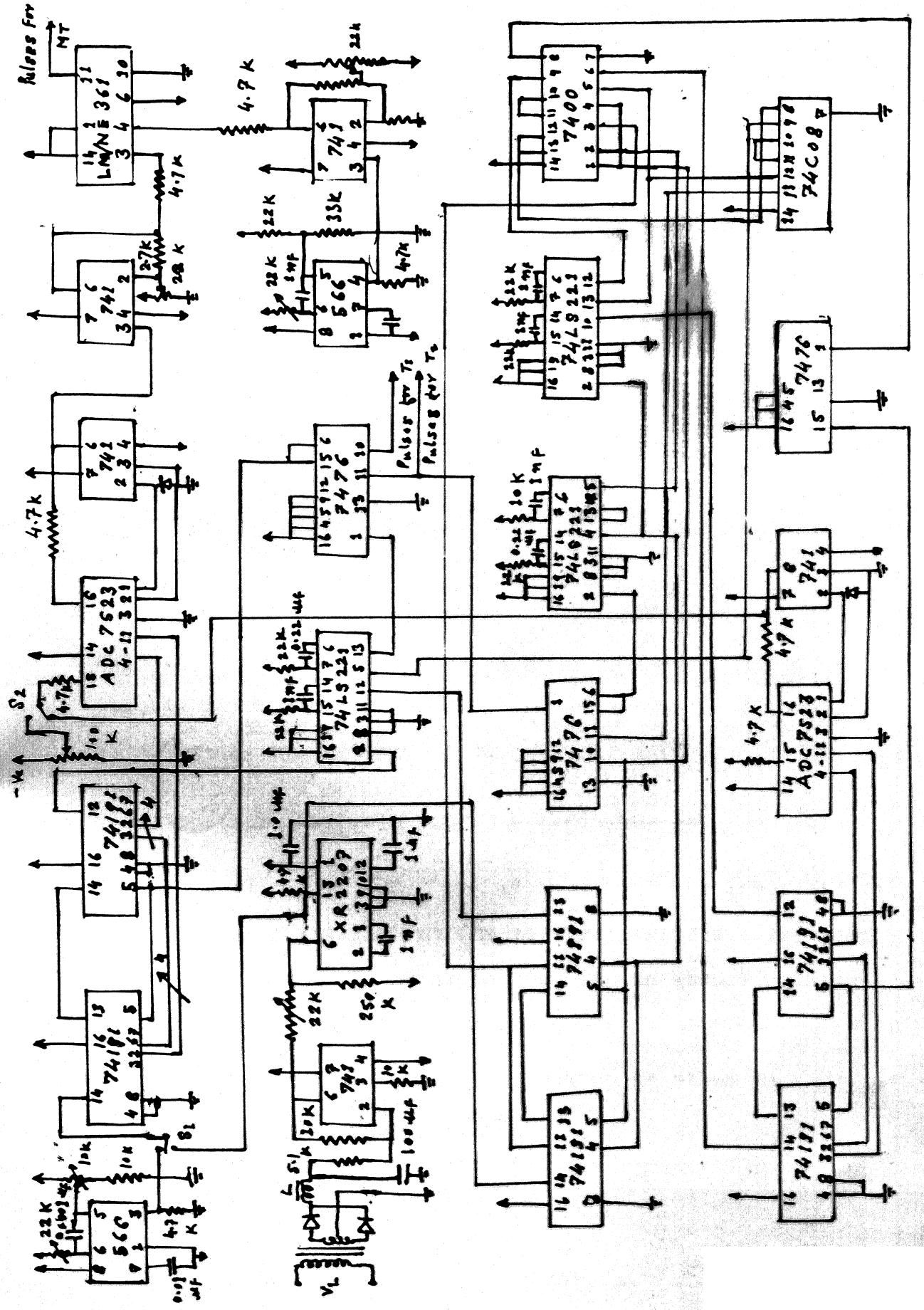
Fig. 4.6.1 Detailed control circuit

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b) Modulation index in open loop and inverter frequency in close loop:

In the case the level of input voltage and power to the motor can be controlled with the help of a potentio-meter, while inverter frequency is decided by the motor terminal voltage so that ratio between them is maintained at 4;4.

c) Modulation index in close loop and inverter frequency in open loop:

In this case input voltage and power to motor are maintained at the maximum possible value by maximum power tracker circuit. The inverter frequency can be controlled by adjusting the setting of the potentiometer.

d) Modulation index and inverter frequency in close loop:

In this case the level of input voltage and power to the motor is maintained at the maximum possible value and inverter frequency is maintained by VCO to keep V/F ratio constant at 4.4.

The complete experimental set up is shown in Fig. 4.6.2.

Plate, Unit b
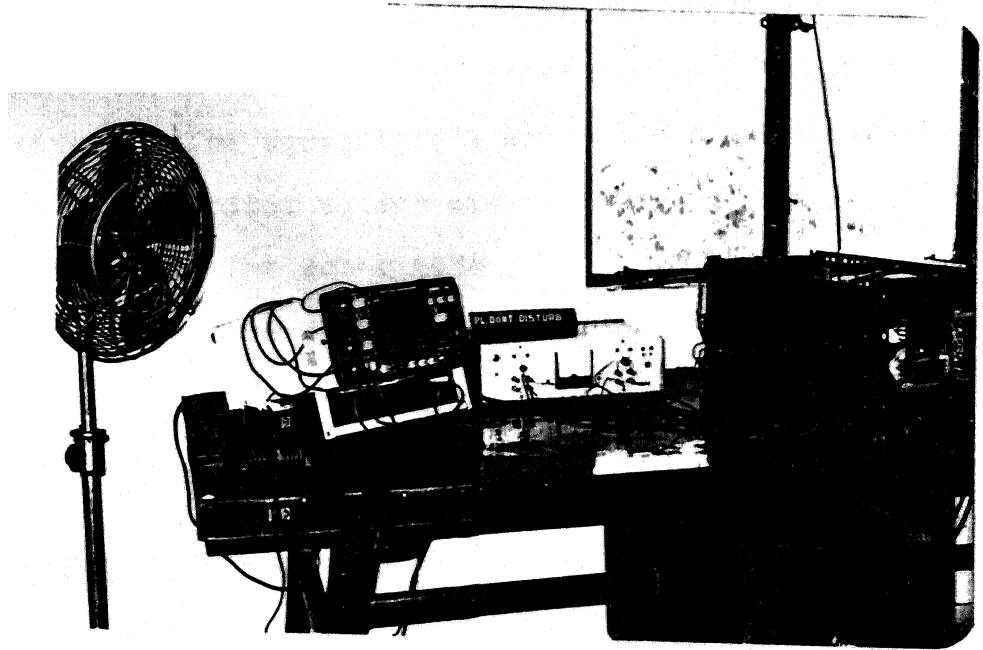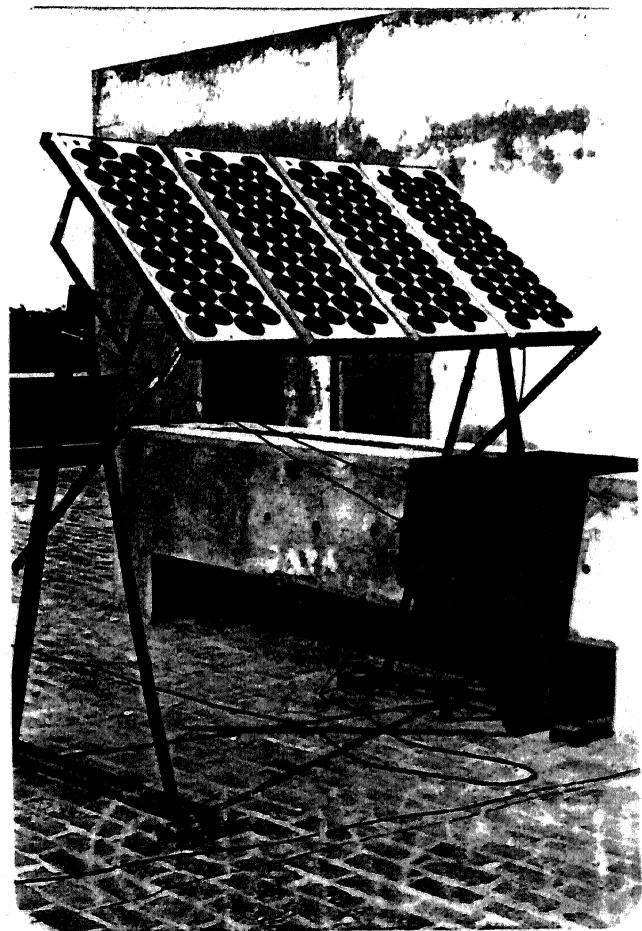
Fig. 3.2 Experimental setup

CHAPTER 5

PERFORMANCE OF THE DRIVE

5.1 ANALYSIS OF SINGLE PHASE PERMANENT CAPACITOR MOTOR

The analysis of permanent capacitor induction motor is some what complicated than other single phase induction motors due to interaction of two fields and dissimilarity of the constants for two windings. Therefore no simple equivalent circuit can be drawn. The author in reference [19] has reported a method for analysis of this type of motor by using cross field theory. The two windings on stator are assumed to be in space quadration. The winding having capacitor in series is designated as start winding. The subscript S and M are used for start and main winding respectively. The subscripts 1 and 2 are used for stator and rotor. All rotor values are expressed in terms of main stator winding. The subscripts y and x are used for rotor currents referred to stator main and start winding respectively.

The following notation are used:

stator main winding impedance $= Z_{1M}$

stator main winding current $= I_M$

stator main winding counter emf $= E_M$

stator main winding magnetic impedance $= ZM$

stator start winding impedance $= Z1S$

stator start winding current $= IS$

stator start winding counter emf $= E_S$

stator start winding magnetic impedance $= ZS$

impedance of capacitor $= ZC$

rotor impedance $= Z2$

rotor current refer to stator main winding $= I_y$

rotor current refer to stator start winding $= I_x$

rotor reactance $= x_2$

start to main winding turn ratio $= a$

speed of rotor per unit synchronous speed $= S$

The following fundamental equations can be written.

For start main winding

$$V = Z_M \ (I_M - I_Y) + I_M Z_{1M} \qquad (1)$$

$\qquad\qquad$ counter emf $\quad$ impedance drop

For stator start winding

$$V = Z_S \ (I_S - I_x) + I_S (Z_{1S} + Z_C) \qquad (2)$$

$\qquad\qquad$ counter emf $\quad$ impedance drop

For rotor refer to main winding

$$\angle_M(I_M-I_Y) + S[j\ \frac{Z_S}{a}\ (I_S-I_x) + aI_x x_2]-I_y Z_2 = 0 \qquad (3)$$

    transformer voltage   speed emf   impedance drop

For rotor refer to start winding

$$\frac{\angle_S}{a}\ (I_S-I_x) + S[-j\ Z_M(I_M-I_Y) - I_y\ x_2] - aI_x\ z_2 = 0 \qquad (4)$$

    transformer   speed voltage   impedance drop
    voltage

    These four equations can be solved for I_M, I_S, I_Y and I_x than the performance of the motor can be calculated as follows.

Counter emf in main winding $EM = V - I_M\ Z1M$

Counter emf in start winding $ES = V-I_S(Z1S+ZC)$

The rotor input or power transfered across the air gap is:

$$EMI_Y\ \cos\ (EM,IY) + ES\ I_x\ \cos\ (ES,I_x)$$

Power converted in to mechanical power = power transfered

                                   across the air gap -

                                   rotor copper loss

$$PM = EMI_Y\ \cos\ (EM,IY) + ESI_x\ \cos\ (ES,I_x) - (I_y^2+a^2 I_x^2)R_2$$

Net output = PM — friction and windage loss

The torque in synchronous walls tt can be given as

$$a\ EM\ I_x \sin(EM,I_x) + \frac{ES}{a} I_y \sin (ES,I_y)$$

and the stator input is

$$\rightarrow V\ IM \cos (V,IM) + V\ IS \cos (V,IS)$$

total supply current

$$I = IM + IS$$

hence power factor $= \cos (V,I)$

Two motors were analysed by using this method. The characteristics are shown in Fig. 5.1.1 and 5.1.2 for Motor I and Motor II respectively. The parameter of the motors were obtained from the no load and block rotor tests and are given in Appendix I. In the characteristics of motor I, it can be noted that the variation of the input current and power with speed is unusual. This may be due to small size of machine.

5.2 PERFORMANCE OF INVERTER

The inverter was tested on different types of loads namely resistive, RL and single phase permanent capacitor motor. The oscillograms of the output and input currents and voltages are shown in Fig. 5.2. This figure also shows

Characteristics of 1 ph. permanent capacitor induction motor
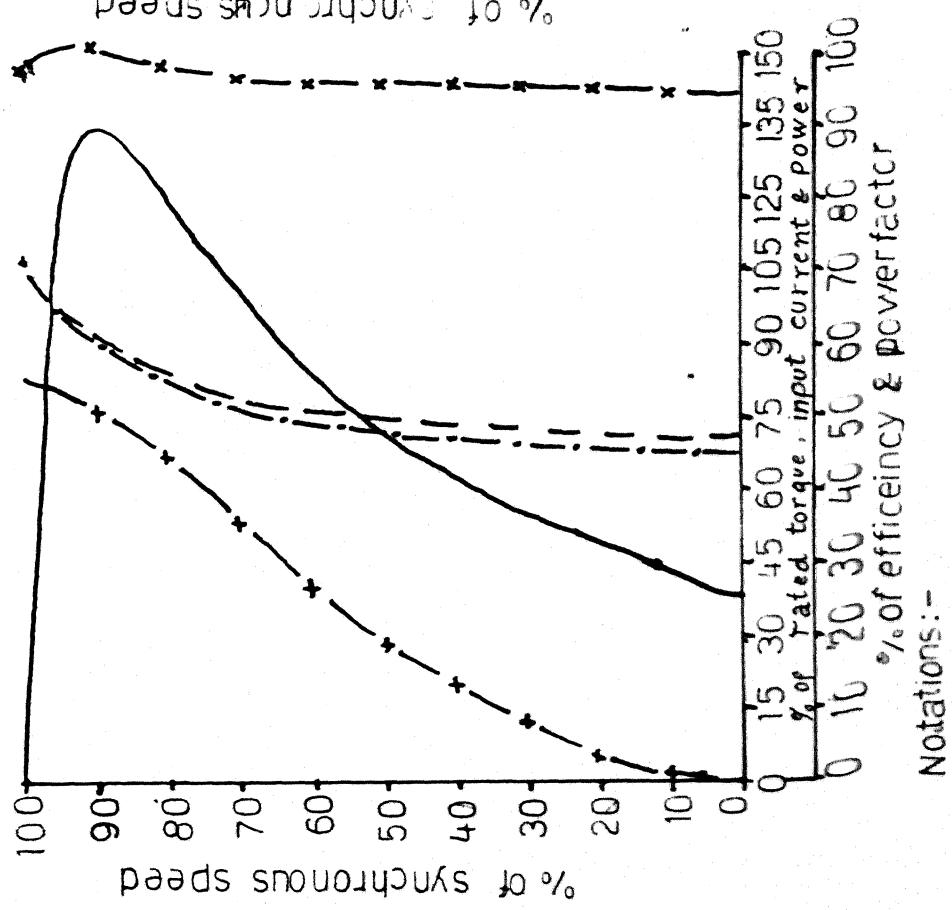
Fig. 5.1.2 Motor II

Notations:-
torque :-
input power :-
input current :-

Fig. 5.1.1 Motor I

% of efficeincy & power factor
power factor :-
efficeincy :-

65
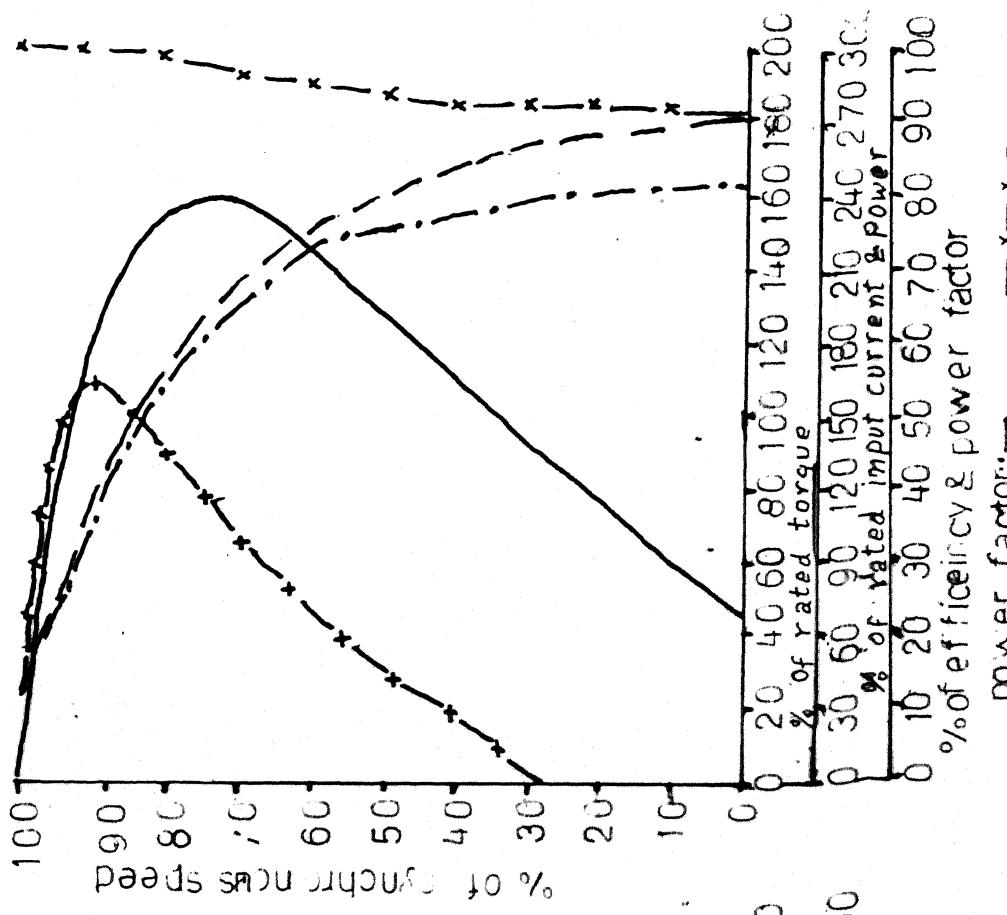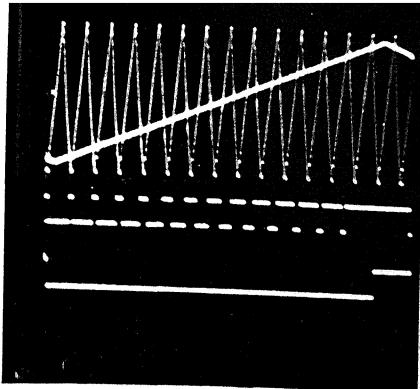
a. Firing circuit waveforms

From top:-

(i)   Carrier wave (2V/div)
(ii)   Modulating wave (2V/div)
(iii)   PWM pattern (5 V/div)
(iv)   Up-down signal to counter
        (5 V/div)
        time scale: 0.2 msec/div.

b. Waveforms of inverter with
   resistive load (200 ohms).

From top:-

(i)   Input current (0.166 A/div)
(ii)   Input voltage (5 V/div)
(iii)   Output voltage (50 V/div)
(iv)   Output current (0.416 A/div)
        time scale : 5 msec/div.
        reference level for DC:bottom
        line of graph.
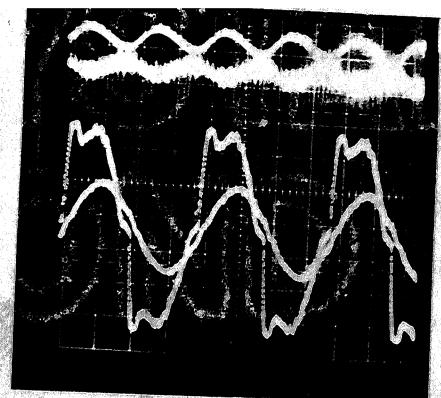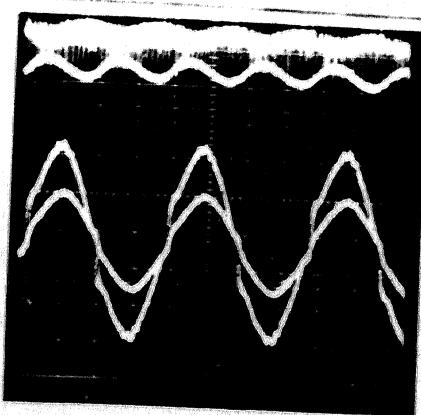
c. Waveforms of inverter
   with R-L load (200 ohms,
   415 mH)

From top:-

(i)   Input voltage (5 V/div)
(ii)   Input current (0.166 A/div)
(iii)   Output voltage (50V/div)
(iv)   Output current (0.416A/div)
        time scale: 5 msec/div.
        reference level for DC:
        bottom line of graph.

d. Waveforms of inverter with
   single phase capacitor run
   Induction motor.

From top:-

(i)   Input current (0.166 A/div)
(ii)   Input voltage (10 V/div)
(iii)   Output voltage (100 V/div)
(iv)   Output current (0.416 A/div)
        time scale: 5 msec/div
   reference level for DC:
        bottom line of graph.
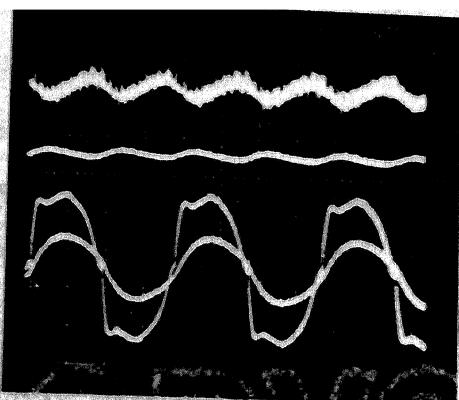
Fig. 5.2.1 Oscillograms of inverter performance

an oscillogram of the half cycle of the PWM pattern. From
the oscillograms, it can be seen that the output current
wave shape is independent of the type of load and is very close
to sinusoidal. The output voltage waveform depends upon the
type of load. In the case of motor load, it is close to
sinusoidal. However at the lower modulation index and
frequency, considerable distortion in the output voltage and
current wave forms was found. This may be due to use of triangular
reference waveform instead of sinusoidal. The ripples in the
input voltage and currents are considerably low.

5.3 PERFORMANCE OF DRIVE

In the present drive, two speed control schemes, namely
stator voltage control at fixed frequency and constant V/F
ratio control are implemented. A maximum power tracker circuit
is used to maximize the input power to the motor by controlling
the modulation index. In order to check the performance of the
maximum power tracker circuit, option for open loop control
of the modulation index is also provided. Since short circuit
current of the solar cell is proportional to the intensity
of the light, the speed of the fan, power input to motor and
power output of PV array are measured at different values of
short circuit current by using both schemes of the speed contro

with and without maximum power tracker circuit, and are given in table I. When maximum power tracker is not used, the input power to the motor is adjusted to a maximum value with the help of potentiometer.

From the results of Table I, it can be seen that maximum power tracker is capable of maintaining the input power to the motor within 2% of the 'maximum value'. However it did not make full use of maximum available PV power, especially at low power levels. At low insolation levels stator voltage control with fixed frequency gives higher speed of the fan than the constant V/F ratio control. While at higher insolation levels constant V/F ratio gives better results. This may be due to the fact that the current required by motor with constant V/F ratio may be more than that with fixed frequency stator voltage control at low speeds, which may force the array to operate at lower voltage and power levels. Since the input current to the motor attains a maximum value at about 2/3 of synchronous speed with stator voltage control, the required current may be more than that with constant V/F ratio at higher insolation levels. This may be the reason of lower speeds at higher insolation level with stator voltage control. Sinceth the power output of the

Table 1: EXPERIMENTAL RESULTS

Short circuit current Amp.	Max. available power Watts	Stator voltage control						Constant V/F ratio constant					
		with maximum power tracker			Manual			with maximum power tracker			Manual		
		Power output of PV array W	Input Power to the motor W	Speed of fan rpm	Power output of PV array W	Input power to the motor W	Speed of fan rpm	Power output of PV array motor W	Input power to the motor W	Speed of Fan rpm	Power output of PV array W	Input power to PV motor array W	Speed of the fan rpm
.78	32.0	22.0	10.0	61	22.0	10.0	.62	14.0	4.0	-	13.0	4.0	-
.02	49.0	36.0	19.0	375	37.0	19.0	360	35.0	11.0	160	36.0	11.0	180
.12	52.0	52.0	21.0	330	51.0	20.0	340	30.0	12.0	120	42.0	15.0	240
.14	50.0	41.0	20.0	270	41.0	20.0	265	27.0	8.0	30	30.0	12.0	95
.18	54.0	51.0	22.0	540	50.0	22.0	525	50.0	22.0	836	50.0	21.0	782
.30	60.0	56.0	28.0	780	57.0	29.0	790	62.0	28.0	1000	63.0	32.0	1007
.33	60.0	55.0	2760	732	57.0	28.0	740	55.0	27.0	932	56.0	27.0	920
.41	62.0	60.0	31.0	840	61.0	32.0	880	65.0	32.0	1037	65.0	33.0	1045
.48	64.0	64.0	32.0	862	64.0	32.0	856	64.0	28.0	1070	64.0	24.0	1080
.51	66.0	65.0	34.0	990	66.0	38.0	970	66.0	36.0	1090	65.0	36.0	1090

fan is proportional to the cube of its speed and short
circuit current of a ~~roter~~ solar cell is proportional ~~the~~ to
the intensity of the light, a direct relation between
power output of fan and intensity of light can be
obtained from Table I.

CHAPTER 6

CONCLUSIONS

A photovoltaic induction motor drive was built and tested in the laboratory with a fan load. A maximum power tracker was used to maximize the input power to the motor. The suitable speed control schemes were used to ensure good efficiency of the motor. The performance of the maximum power tracker was found to be satisfactory. The results reveal that at low insolation level, stator voltage control gains higher motor speed, while constant V/F ratio control gives better results at higher insolation levels. The analysis of the system for efficiency and operation of drive with pump could not be under taken due to limitation of time and unavailability of pump in desired ratings. However the test on the fan in lab. indicates that drive scheme is suitable for small photovoltaic pump systems.

The present scheme has certain disadvantages which require further investigations. In this scheme stepped triangular reference modulation waveform was used to generate PWM patte which results not only in distortion of the output voltage and current waveforms of inverter at low values of modulation index and frequency but also affects the performance of VCO and maximum power tracker circuit, because the relation betwe

peak and rms values of motor terminal voltage does not remain
the same for all values of modulation index. This problem
wan easily be eliminated by using sinusoidal reference wave
instead of stepped triangular. Further more at low ~~radiation~~ insolation
levels, none of the speed control scheme ensures full utili-
zation of the maximum ~~variable~~ available photovoltaic power. A speed
control scheme may be investigated which should control the
speed of drive in such a way that the current required by the
motor should be slightly, less than the photovoltaic current
corresponding to the maximum power point at all insolation
levels and temperatures. Further more to ensure maximum
mechanical output (water), speed of the drive can be maximized
instead of input voltage to the motor. It will be interesting
to perform efficiency analysis of induction motor pump systems
and its comperision with other available PV pump drive
systems.

APPENDIX I

RATINGS AND PARAMETERS OF MOTORS

Motor I

 hating 220/240 volts, 40 Watt padstal fan

Parameters

stator main winding resistance RIM = 189.87 ohm

stator main winding reactance XIM = 237.056 ohm

stator main winding magnetizing reactance XMM = 1025.31 Ohm

Stator start winding resistance RIS = 229.665 ohm

stator start winding reactance XIS = 266.879 ohm

stator start winding magnetizing reactance XMS = 2031.39 ohm

reactance of capacitor XC = 1327.258 ohm

equivalent series resistance of capacitor RC = 4.896 ohm

rotor resistance refer to stator R_2 = 130.122 ohm

rotor reactance refer to stator X_2 = 237.056 ohm

equivalent core resistance of main winding RMM = 7523.9061 ohm

equivalent core resistance of start RMS = 14905.18 ohm

Startion mainwinding turn ratio a = 1.4075 ohm

friction and windage $\not{o}$ loss = 1.50 watts.

Motor II

0.25 HP, permanent capacitor induction motor and centrifugal pump in mono block.

Ratings

220/240V, 50 Hz, 1.8A, 2700 rpm, 0.25 HP, 4.5/14 mt, 64/28 lpm

Parameters

stator main winding resistance RIM = 19.04 ohm

stator main winding reactance XIM = 11.028 ohm

stator main winding magnetizing reactance XMM = 299.027 ohm

stator main core loss equivalent resistance RMM = 1174.32 ohm

stator start winding resistance RIS = 18.904 ohm

stator start winding reactance XIS = 9.9116 ohm

stator start winding magnetizing reactance XMS = 344.50 ohm

stator start winding core loss equivalent resistance RMS = 1025.6

rotor resistance refer to stator side R_2 = 19.54 ohm

rotor reactance refer to stator side X_2 = 11.028 ohm

reactance of capacitor XC = 344.50 ohm

equivalent series resistance of capacitor RC = 8.277 ohm

friction and windage loss FWL = 29.0 watts.

where,

$$ZIM = RIM + j\ XIM$$

$$ZM = RMM // j\ xMM$$

$$ZIS = hIS + j\ xIS$$

$$ZS = RMS // j \times M$$

$$ZC = hC + j\ xC$$

$$Z_2 = h_2 + j\ x_2$$

REFERENCES

[1] Buresch, Mathew, 'Photovoltaic Energy Systems',
McGraw-Hill Book Company,1983.

[2] Green Martin A., 'Solar Cells', Prentice Hall Inc.
Englewood Cliffs, N.J. 1982.

[3] S.M. Sze, 'Physics of semiconductor devices', Wiley
Eastern Ltd. 1985.

[4] Chenming HV, Richard M. White, 'Solar Cells from
Basic to Advance Systems', McGraw-Hill Book Company,
1983.

[5] Bimal K. Bose, Paul M. Szezesny and Robert L. Steigerwald,
'Microcomputer control of a residential photovoltaic
power conditioning system', IEEE Trans on Ind. App.
vol. IA-21, No. 5, pp. 1182-91, Sept/Oct. 1985.

[6] Urs Boegli and Remo Ulmi, 'Realization of a new inverter
circuit for direct photovoltaic energy feedback into
the public grid', IEEE Trans. on Ind. App., vol. IA-22,
No. 2, pp. 255-58, March/April,1986.

[7] 'Small scale solar-powered irrigation pumping systems
phase I project report', UNDP Project GLO/78/004,
Executed by the World Bank, July,1981.

[8] G.K. Dubey and W.G. Dunford, 'Solar Pump drives', A
project report, University of British Columbia.

[9] J. Appebbaum and J. Bany, 'Performance analysis of d.c.
motor photovoltaic converter system-I seperately excited
motor, Solar Energy, vol. 22, No. 5, pp. 439-445, 1979.

[10] J. Appebaum, 'Performance analysis of dc motor photovoltaic
converter system-II semies and shunt excited motors',
solar energy, vol. 27, No. 5, pp. 421-431, 1982.

[11] A. Braunstein and A. Kornfield, 'Analysis of Solar
Powered electric water pumps', Solar energy vol. 27,
No. 3, pp. 235-240, 1981.

[12] Joseph R. Pottebaum, 'Optimal characteristics of a
variable frequency centrifugal pump motor drive',
IEEE Trans. on Ind. App., vol. IA-20, No. 1,
pp. 23-31, Jan/Feb. 1984.

[13] Cyril G. Veinott, 'Fractional and subfractional horse
power electric motors', McGraw-Hill Book Company,
1970.

[14] P. Savary, M. Nakaoka and T. Maruhashi, 'Novel type of
high frequency link inverter for photovoltaic residential
applications, IEE Proc. vol. 133, Pt. B, No. 4, pp.
279-284, July,1986.

[15] Milsuyuki Hombu, Shijeta Veda, Akiteru Veda and Yasud Matsu
'A New current source GTO inverter with sinusoidal output
voltage and current.

[16] Wood Peter, 'Switching Power Converter', Van Nostrand
Reinhold Company,1981.

[17] E.T. Calkin and B.H. Hamitton, 'Circuit techniques for
improving the switching loci of transistor switches
in switching regulators', IEEE Trans on Ind Appl.,
vol. IA-12, No. 4, pp. 364-69, July/Aug. 1976.

[18] E.T. Calkin and B.H. Hamilton, 'A conceptually new
approach for regulated DC to DC converters employing
transistor switches and pulse width control', IEEE
Trans. on Ind. Appl., vol. IA-12, No. 4, pp. 369-77,
July/Aug. 1976.

[19] A.F. Puchstein, T.C. Lloyd and A.G. Conard, 'Alternating -
current machines', Third edition, John Wiley and Sons,
Inc., New York,1960.

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